



Benthic Processes are an Important Indicator of Eutrophication in Intermittently Open and Closed Lakes and Lagoons

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Abstract

Intermittently open and closed lakes and lagoons (ICOLLs) are globally important estuarine systems that are separated from the ocean by a sand beach barrier or berm. The barrier may open or close naturally because of sand and sediment movement or be manually opened by estuarine managers in times of flooding. As intermittently closed systems, it is important to understand the potential for eutrophication and what are the best indicators. This study investigated water quality, sediment quality and benthic processes in four shallow ICOLLs in Sydney, Australia, that experience a range of nutrient loadings. Manly and Curl Curl Lagoons experience higher turbidity and concentrations of pelagic Chl-*a* compared to Dee Why and Narrabeen Lagoons. They also differ with respect to general morphology with Manly and Narrabeen deeper and more linear while Curl Curl and Dee Why are shallower and more circular. Relationships between nutrient loading and traditional water quality indicators of eutrophication such as chlorophyll-*a*, turbidity and dissolved oxygen appeared to be moderated by lagoon morphology and hydrology, which control the ratio of pelagic to benthic production and net accumulation of sediment organic matter. We found that all the lagoons investigated were net heterotrophic, with Narrabeen and Manly the least and the most heterotrophic respectively. Ratios of total organic carbon (TOC):benthic community respiration (CR) varied among lagoons and were likely related to the dominance of refractory organic matter in Narrabeen (~99%), and more labile organic matter in Manly and Curl Curl Lagoons (~90%). Benthic community respiration increased with nutrient loading rates across the lagoons, suggesting that benthic processes are a critical indicator of eutrophication in these shallow systems. In contrast to the generalised conceptual model of eutrophication in coastal systems whereby nutrient pollution causes a reduction in benthic primary productivity at the expense of increased pelagic primary productivity, our results suggest that benthic microalgal productivity in shallow ICOLLs plays an important role in buffering against eutrophication of the water column but may also contribute to organic enrichment of sediments.

Keywords ICOLLs · Nutrient · Morphology · Hydrodynamics · Eutrophication

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Introduction

Nutrient (nitrogen and phosphorus) enrichment of coastal systems due to point source and diffuse pollution is a worldwide problem, resulting in various impacts including toxic algal blooms, hypoxia, trophic disturbances and system-state shifts (Andersen et al. 2006; Cloern 2001; Malone and Conley 1996; Richardson and Jørgensen 1996). These impacts are known collectively as eutrophication, which has been broadly defined as an increase in the rate of organic matter supply to an aquatic ecosystem (Nixon 1995; Pinckney et al. 2001). This most commonly occurs due to the stimulation of primary production by increased nutrient loading, leading to biomass accumulation, a concomitant increase in heterotrophic microbial metabolism,

and a cascade of biogeochemical (e.g. reduced denitrification efficiency) and ecological impacts (Glibert et al. 2011; Paerl et al. 2014). Some of the ways that eutrophication is expressed in a system include algal blooms and altered food webs. Blooms may lead to hypoxia and anoxia, loss of biodiversity and fish kills, decreased water clarity and noxious odours (Rabalais et al. 2009).

Estuarine morphology influences the nature of ecological response to nutrient loadings and hence expressions of eutrophication. In general, deeper systems tend to be dominated by pelagic productivity and heterotrophic sediments, while the importance of benthic productivity (e.g. due to seagrasses and benthic microalgae) is proportionately greater in shallow systems (Crawshaw et al. 2019; Ferguson et al. 2003). Accordingly, eutrophication in the former is expressed as a prevalence of phytoplankton blooms (McGlathery et al. 2007; Wallace and Gobler 2021), while in the latter the risk is more associated with macroalgae (Teichberg et al. 2010; Valiela et al. 1997). This diagnostic is further complicated by the occurrence of algal blooms in relatively undisturbed systems due to changes in factors such as temperature and sunlight (Scanes et al. 2020). Hydrodynamics also play a key role in ecological responses, for example water residence times determine the rate of biomass accumulation within a system and therefore control important feedbacks such as nutrient recycling from the sediments and denitrification efficiency (Crawshaw et al. 2019; Hyman and Stephens 2020).

The overall expression of eutrophication also varies greatly across the spectrum of coastal aquatic systems worldwide due to differences and interactions among climatic, morphological, hydrological and biogeochemical controlling factors (Hughes et al. 2011; Murrell et al. 2018; Plew et al. 2020). Climate (e.g. rainfall seasonality), geographical setting (e.g. catchment size, coastline geology) and oceanic boundary conditions (e.g. wave exposure climate and tidal range) play important roles in determining the morphology of estuarine systems (Roy 1984; Roy et al. 2001), giving rise to distinct estuarine ‘types’ that share common hydrodynamic features (Valle-Levinson 2010). These in turn determine the impacts of nutrient loads and ultimately the susceptibility of a system to eutrophication (Lemley et al. 2024; Painting et al. 2007). For example, the resultant concentration of a point source nutrient input depends on hydrodynamic factors such as the volume and residence times of receiving waters (Eyre 2000; Nel et al. 2023). In addition, tidal exchange of water across downstream boundaries (e.g. the ocean entrance of an estuary) results in ebb-tide export of pollutants and dilution due to flood-tide ingress of oceanic water (Ferguson et al. 2004; McKee et al. 2000). Yet the various eutrophication assessment methodologies applied by different countries do not generally incorporate hydrology

or morphology into models that assess risk of eutrophication occurring or assess indicators such as benthic processes. For example, the Assessment of Estuarine Trophic Status (ASSETS) model is useful as a screening tool, but limited to external forcings (nutrient loading) and associated symptoms (Bricker 1999). Further, the Comprehensive Procedure (COMPP) developed as part of the 1992 OSPAR Convention (named for the Oslo Convention 1972 and Paris Convention 1974) seeks to identify no problem, potential problem and problem areas in relation to eutrophication, but similarly focuses on nutrient inputs/concentrations and effects mainly occurring in the water column (e.g. phytoplankton blooms, fish kills) (Claussen et al. 2009). Therefore, these approaches may not be sufficient for all estuaries.

Intermittently closed and open lakes and lagoons (ICOLLs) are a distinct type of estuary found along high-energy coastlines of southeast Australia, Mexico, Sri Lanka and South Africa (McSweeney et al. 2017). They are also prevalent in other areas with Mediterranean-like climates such as Spain, Portugal, California and Texas (Largier 2023). They are characterised by the periodic closure of the ocean entrance due to the ingress of marine sand driven by tide and wave energy. While the entrance is closed, water levels primarily vary in response to freshwater inputs and evaporation, with entrance breakout occurring once water levels exceed that of the entrance berm (Haines 2006). Aside from this defining feature, ICOLLs comprise a diverse range of morphologies of varying size, depth and plan shape. These morphological features are thought to have profound influences on hydrodynamic processes and therefore water quality, with relatively linear systems termed ‘displacement-dominated’ ICOLLs due to a tendency for catchment inflows to displace resident water in the system during entrance breakout (Haines 2006). In contrast, more circular systems are known as ‘mixing-dominated’ ICOLLs as freshwater inflows are mixed with resident water by wind-driven wave energy and currents before being exported to the ocean (Haines et al. 2006).

This study focuses on four ICOLLs located along the northern metropolitan coastline of Sydney, Australia: Manly, Curl Curl, Dee Why and Narrabeen Lagoons. Varying degrees of urbanisation in their catchments have resulted in significant increases in nutrient loading and the potential for eutrophication. However, traditional indicators such as phytoplankton blooms and reduced water clarity may not be appropriate to assess eutrophication since they also occur in undisturbed systems. Despite some ‘red flags’ such as reports of high turbidity and concentrations of pelagic Chl-*a* in Manly and Curl Curl compared to Dee Why and Narrabeen that suggest some systems may be at a tipping point with respect to eutrophication (DPIE 2021), routine monitoring in these systems as part of the state government

Monitoring, Evaluation and Reporting (MER) program has not revealed obvious trends in association with diffuse pressures. This complicates the ability of managers to interpret routine data based on a conceptual understanding of biogeochemical function, and to identify indicators of eutrophication.

The overall aim of this study was to investigate how physical forcings such as hydrology and morphology interact with catchment nutrient inputs to influence indicators of eutrophication in coastal lagoons. We present here an intensive survey of water quality (including turbidity, dissolved oxygen and Chl-*a*), sediment quality (including particle size and organic matter) and benthic process rates (e.g. primary productivity, respiration) across the four study ICOLLs. We hypothesised that each lagoon would accumulate nutrients as a function of morphological and hydrological characteristics and indicators of eutrophication would vary accordingly. We expected that deeper

lagoons would accumulate more nutrients as they are unlikely to drain completely when open to the ocean. In contrast, shallower lagoons may be more easily flushed and would be less likely to accumulate nutrients. We also expected that lagoons with a more circular shape have greater mixing and homogenisation of nutrients compared to linear systems where we expected differences in the accumulation of nutrients with distance from the opening. As a consequence, we expected the potential for eutrophication to be higher in linear, deeper systems and with distance from the lagoon opening.

Study Area

Narrabeen, Dee Why, Curl Curl and Manly Lagoons are located along the northern beaches' coastline of Sydney, Australia (Fig. 1). The region experiences a warm temperate

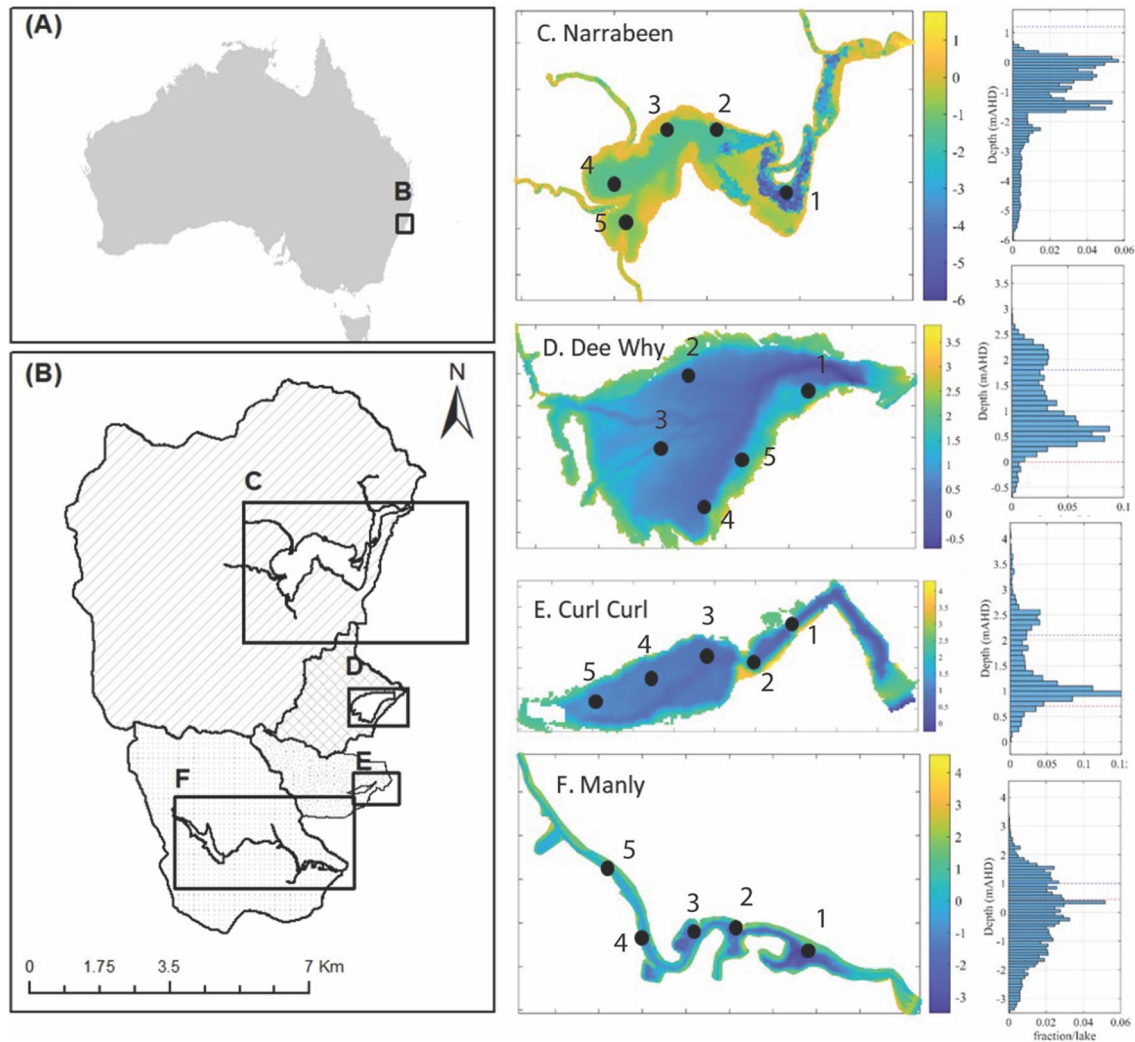


Fig. 1 A and (B) Location of the study area; (C–F) bathymetry and hypsometry of the study ICOLLs and sites within

climate, with rainfall tending to be highest during Autumn months when storms associated with deep low-pressure systems form off the coast. All four study systems are classified as ICOLLs, although their entrances are now actively managed: Dee Why, Narrabeen and Curl Curl Lagoons are artificially opened at predefined water level thresholds to alleviate flooding in fringing urban areas, while Manly Lagoon is effectively permanently open via a concrete culvert across the entrance berm (Table 1). The catchment size and degree of urbanisation vary across the systems (Table 1). The ICOLLs are all relatively shallow (mean depths < 2 m); however, two of the systems (Manly and Narrabeen Lagoons) have deeper basins that extend below mean sea level (Fig. 1). Manly has been extensively dredged in the past. Manly and Narrabeen Lagoons have limited areas of seagrass (*Zostera muelleri*) located on shoals adjacent to the ocean entrance, and all lagoons are periodically subject to ephemeral growth of macroalgae (Eyre and Ferguson 2002). Five sites were selected in each lagoon at increasing distances from the lagoon opening, apart from in Dee Why where the circularity and depth constrained sites to around the edges (Fig. 1).

Methods

Analytical procedures, abbreviations and average variation coefficient (CV) of triplicates are summarised in Supplementary Table S1.

Catchment Loads

Annual average freshwater inputs were estimated using the 2CSalt model (Gilfedder et al. 2007), incorporating land use and digital elevation layers from 2017. Diffuse loads of total nitrogen (TN) and total phosphorus (TP) were estimated by integrating freshwater inflows and land use export coefficients from the major sub-catchments (Roper et al. 2011). The lagoons do not receive any loading from wastewater discharges. TN and TP loads were then normalised according to the mean volumes and areas of ICOLL basins (Table 1).

Morphometrics

ICOLL hypsometry and bathymetry are presented in Fig. 1, and morphometric parameters derived from these data are

Table 1 Morphometric and nutrient loading attributes of the study systems. Thalweg length joins the lowest points along the entire length of a stream bed or valley in its downward slope, defining its deepest channel

		Narrabeen	Dee Why	Curl Curl	Manly
Metrics	Waterway area (km ²)	1.7	0.3	0.1	0.1
	Catchment area (km ²)	51.23	8.27	2.02	12.70
	% urban intensive use*	48	96	95	76
	Mean depth (m)	1.4	0.5	0.4	1.1
	Volume (ML)	3405	176	28	154
	Perimeter length (m)	21,724	3714	1693	5565
	Thalweg length (m)	4945	980	1111	2420
	Mean width (m)	255	266	73	34
	Thalweg:width	19	4	15	72
	Opening levels (m AHD)	1.0–1.3	2.2	2.2	1.4
Hypsometry	0–0.5 m	5%	37%	50%	24%
	0.5–1.0 m	22%	52%	44%	20%
	1.0–1.5 m	20%	9%	6%	16%
	1.5–2.0 m	15%	2%	0%	15%
	> 2.0 m	39%	0%	0%	25%
	vol < 0 m AHD	58%	1%	0%	53%
area < 0 m AHD	64%	2%	0%	62%	
Loads	Total annual flow (ML)	13491	3825	956	5225
	TP load (t year ⁻¹)	1.1	0.6	0.1	0.7
	TP load/vol (g P m ⁻³ year ⁻¹)	0.0003	0.0034	0.0046	0.0048
	TP load/area (g P m ⁻² year ⁻¹)	0.6	2.2	2.3	6.6
	TN load (t year ⁻¹)	9	3	1	5
	TN load/vol (g N m ⁻³ year ⁻¹)	0.003	0.020	0.025	0.030
TN load/area (g N m ⁻² year ⁻¹)	5	13	13	42	

*From NSW Landuse 2013 – Seed (2017). <https://datasets.seed.nsw.gov.au/dataset/nswlanduse-2013>. ML refers to megalitres or 1000 m³. m AHD refers to metres in Australian Height Datum

presented in Table 1. Mean water levels were estimated from analysis of hourly water level data from each system between 2015 and 2018 (sourced from Manly Hydraulics Laboratory (2019)), and these were integrated with bathymetry data to estimate mean water depths (Table 1). Plan shapes ('linearity') were estimated as the ratio of waterway area/perimeter length, while the degree of shoaling was estimated as the ratio of waterway area/mean depth (Haines et al. 2006). These ratios were selected to assist in describing the morphology and hydrodynamics of the ICOLLs as the ratios indicate whether the ICOLL was linear or circular and bathymetry which influences shoaling.

Water Quality

Water quality in the lagoons was monitored fortnightly between 31st October 2017 and 19th April 2018 to include 6 months prior to benthic process rate measurements in April 2018. This was done as part of the NSW Natural Resources Monitoring, Evaluation and Reporting (MER) Program where protocols have been informed by Roper et al. (2011). Sites were a subset of those sampled for sediments and included sites 1, 3 and 5 in Manly, sites 3 and 4 in Curl Curl, sites 1–5 in Narrabeen and site 3 in Dee Why (Fig. 1). Depth-integrated samples were collected from the top 1 m of the water column using a pole sampler. Sub-samples for chlorophyll-*a* (110 mL) were filtered immediately onto GF/F filter which was stored in the dark at $-20\text{ }^{\circ}\text{C}$ until analysis to prevent pigment degradation. Sub-samples for dissolved nutrients (30 mL) were filtered immediately through Minisart® 0.45-mm cellulose acetate filters and frozen at $-20\text{ }^{\circ}\text{C}$ until analysis for ammonia (NH_4^+), nitrate and nitrite (NO_x), dissolved organic nitrogen (DON), total dissolved nitrogen (TDN), dissolved inorganic phosphorus (DIP), dissolved organic phosphorus (DOP), total dissolved phosphorus (TDP), total nitrogen (TN) and total phosphorus (TP). Water physico-chemical parameters (temperature, pH, salinity, turbidity, fluorescent dissolved organic matter (fDOM), dissolved oxygen) were measured at each site using an EXO2 multiprobe sonde calibrated on the morning of the day of use and deployed at a fixed depth of 40 cm. After each day of sampling, the probe was cleaned with freshwater and data was downloaded from the sonde for visual inspection of errors or data gaps.

Sediment Properties and Benthic Metabolism

Benthic metabolism was estimated from fluxes of O_2 between the sediment and overlying water column measured using undisturbed cores collected in 95 (diameter) \times 500 mm (length) clear acrylic pipe. Triplicate cores (200 mm sediment and 300 mm overlying water) were

collected from five sites representing the main sediment facies within each of the study systems (excluding areas of seagrass, Fig. 1). Incident radiation (2π) was measured at the top and bottom of the water column at each site using a Li-Cor 250 light meter. All light measurements were performed at midday during clear and dry conditions (0 mm rainfall/day, Australian Bureau of Meteorology). Sediment cores were shaded and transported to the laboratory (Northern Beaches Council, Dee Why) within 30 min where they were fitted with a Teflon stir bar assembly and immersed in site water in a temperature-controlled incubator following the NICE protocol (Dalsgaard et al. 2000). Stirring rate was set at just below the threshold for sediment resuspension. Cores were left uncapped for a 6-h pre-incubation period, after which they were fitted with gas-tight plexiglass lids for the commencement of the 3-h dark incubation. The pre-incubation period can be up to 24 h to ensure steady-state concentration profiles (Dalsgaard et al. 2000). Dissolved oxygen concentrations ($\pm 0.01\text{ mg L}^{-1}$) were measured via a sample port in the lid using a Hach Optical oxygen/temperature probe at the start and end of the incubation, after which the lids were removed to allow the cores to freely exchange with site water for approximately 6 h. Cores were then illuminated to in situ light levels using photosynthetically available radiation (PAR) grow lights. After 2 h of illumination, lids were refitted for the commencement of a 3-h light incubation as per the NICE protocol (Dalsgaard et al. 2000). This time period was determined on the basis of previous studies (Ferguson et al. 2003) to be sufficient for measurable changes to water chemistry, without triggering longer-term artifacts due to the over-consumption of O_2 to levels below 20% of initial concentrations (Dalsgaard et al. 2000).

Following the incubations, cores were drained and extruded to sample of the top 5 mm of the sediment surface for total organic carbon, chlorophyll-*a*, carbon and nitrogen concentrations, and grain size. Samples for chlorophyll-*a* extraction were kept in the dark and stored at $-20\text{ }^{\circ}\text{C}$ prior extraction in 90% acetone in 10-mL polyethylene vials. All other samples were immediately frozen at $-20\text{ }^{\circ}\text{C}$ until analysis.

Grain size analyses were performed on wet sediments using a Malvern laser particle size analyser (Mastersizer, 2000) and the fines content (percentage of particles $< 63\text{ }\mu\text{m}$) was obtained using the function 'granstat' in the 'G2Sd' package (Fournier et al., 2014) in R 3.5.1 (R Core Team, 2013).

The content of total organic carbon (TOC) in the sediment was estimated with the loss on ignition (LOI) method (Hyland et al., 2005). Samples were initially dried at $105\text{ }^{\circ}\text{C}$ for 12 h to remove moisture and then organic matter burned in the muffle furnace at $500\text{ }^{\circ}\text{C}$ for 12 h (Wang et al., 2011).

To measure the percentage of total nitrogen (%TN), sediment samples were freeze-dried as explained above and homogenised using a mill grinder (Mixer Mill MM 400). Five to 10 mg (muddy) or 15–20 mg (sandy) sediments were weighed into tin capsules and analysed using Isotope Ratio Mass Spectrometry (IRMS).

Sediment chlorophyll-*a* analyses followed the visible spectrophotometry method with pheo-pigment correction of USEPA Method 446.0 (Arar 1997). Sediment samples were freeze-dried and then rinsed with 30 mL of 90% acetone. Absorbance was read at 665 and 750 nm (UV-6300PC Double Beam Spectrophotometer) before and after the addition of 0.1 N HCl. Acidification technique was used to determine the concentrations of Chl-*a* and pheophytin calculated from equations in Lorenzen (1967). The ratio of benthic:pelagic Chl-*a* was calculated from the sediment sampled in this study and the water quality data collected in the MER Program to investigate whether primary productivity in each system was benthic or pelagic dominated i.e. changed as a function of depth.

Oxygen (O₂) flux rates (μmol.m⁻².h⁻¹) were determined as the difference between the final and initial concentrations in the water column after 3 h incubation (light or dark):

$$Fx = \frac{(Cf - Ci) \times V}{A \times t} \quad (1)$$

where.

Fx flux of oxygen (μmol.m⁻².h⁻¹)

Cf final concentration (μM)

Ci initial concentration (μM)

V volume of water (l)

A surface area (m²)

t incubation time (h)

Benthic community respiration (BCR) and net primary production (NPP) rates were determined from the dark and light incubations respectively. Benthic gross primary production (GPP) was calculated as:

$$GPP = NPP - BCR \quad (2)$$

For practical reasons, it was assumed that BCR in the light equalled BCR in the dark, recognising that light-enhanced respiration is acknowledged to occur in most autotrophs (Raven and Falkowski 1999). Net daily metabolism (NDM) was calculated by averaging BCR and NPP.

Diagenesis Model

A simple model was used to interpret the dark oxygen flux (benthic community respiration; CR) as a function of the organic carbon in the top 5 mm of the sediment (TOC). The model assumes that the TOC pool comprises a labile and a refractory OM fraction, with mineralisation rates (labile_{min} and refractory_{min}) of –100 and –10 mmol C day⁻¹ respectively (Middelburg et al. 1993). The model predicts CR as a function of the TOC pool:

$$CR = OM_{labile} * labile_{min} + OM_{refractory} * refractory_{min} - residual$$

where ‘residual’ is the background oxygen demand due to the reoxidation of reduced chemical species in the sediment profile that arise from anaerobic mineralisation below the top 5 mm of the sediment surface (Jørgensen et al. 2019). This residual was estimated from the mean of the y-intercepts from TOC:CR relationships in each lagoon. Estimations of CR were made for a range of TOC concentrations with 1% and 99% refractory OM, and the resultant TOC:CR for labile and refractory dominated TOC pools was compared with measured data.

Analytical Techniques

All nutrient analyses were carried out colourmetrically using Lachat™ flow-injection analysis. Analytical errors were determined as the average % coefficient of variation of the triplicates. Because the variance of the analytical procedures propagates additively, the variance associated with the nutrient forms calculated by difference was estimated as the sum of the variances of the 2 measured nutrient forms used in the calculation (Eyre 1995). Detection limits for nutrient analysis were calculated using standard additions of certified laboratory standards in both Milli-Q and low-nutrient seawater (Supplementary Table S1).

Statistical Analyses

Analyses of sediment and benthic metabolism variables were done in R (version 4.3.3) (R Core Team, 2013). We investigated how sediment characteristics and benthic metabolism change between lagoons (Lagoon) and distances from the lagoon entrance (Site) with general linear models (GLM). Lagoons and Sites were treated as fixed factors since we were interested in changes in response variables with distance from the lagoon entrance. Residual and qqplots were used to check the homoscedasticity and normality assumptions of the data using the R package ‘DHARMA’ (Hartig and Hartig 2017). TN was logit transformed and CR and GPP were log-transformed to improve residual plots. A negative binomial distribution was assumed for TOC, Chl-*a* and

pheophytin while a Gaussian distribution was used in analyses of CR and GPP. All other variables met assumptions and analyses were done on untransformed data. *p*-values were obtained using the Anova function in the R package ‘car’ (Fox et al. 2012). Significant differences were investigated pairwise comparisons using the R package ‘emmeans’ (Lenth and Lenth 2018) (Supplementary Table S1). To investigate relationships between different variables, we analysed Pearson’s correlations and each lagoon was analysed separately. Principal components analysis (Primer v 6.1.15) was carried out to explore broader correlations between lagoon morphometrics, water quality, sediment characteristics and benthic metabolism. Input data for morphometrics and water quality were lagoon means (standard deviations are reported in tables where relevant).

Results

Morphometrics

Based on morphometric attributes (Table 1), the study systems fall into two groups: deeper systems with a central basin extending below mean sea level (Narrabeen and Manly Lagoons); and shallow systems with a poorly defined central basin sitting above mean sea level (Dee Why and Curl Curl Lagoons). The deeper systems have a greater proportion of their surface area below 1 m deep (at mean water level), while the shallow systems are dominated by shoals less than 1 m deep at mean water level (Table 1). Plan

shapes (‘linearity’ as estimated by waterway area/perimeter) range from relatively circular (Dee Why) to linear (Manly; Table 1).

Water Quality

Water quality for the 6 months leading up to the benthic surveys is summarised in Table 2. Mean salinities ranged from 16.7 in Curl Curl Lagoon to 33.5 in Narrabeen Lagoon. Mean chlorophyll-*a* concentrations were relatively high in Manly Lagoon (13.1 mg L⁻¹) compared to the other three lagoons (4.8, 6.1, 7.2 mg L⁻¹; Dee Why, Curl Curl, Narrabeen). Turbidity was below 6 NTU in all lagoons with minimum observed in Dee Why and maximum observed in Narrabeen. Mean total nitrogen (TN) concentrations ranged from 611 mg L⁻¹ in Narrabeen to 931 mg L⁻¹ in Curl Curl and were dominated by dissolved organic nitrogen (DON; 49–64%). Urea accounted for between 9 and 16% of DON concentrations and was highest in Curl Curl Lagoon. Mean ammonium (NH₄⁺) and nitrate/nitrite (NO_x) concentrations were highest in Curl Curl Lagoon and lowest in Narrabeen Lagoon compared to the other lagoons, with overall dissolved inorganic nitrogen (DIN = NH₄⁺ + NO_x) accounting for between 5 and 25% of TN concentrations.

Total phosphorus (TP) concentrations ranged from 30 to 47 mg L⁻¹ and were dominated by dissolved organic phosphorus (DOP; 41–62%). Dissolved inorganic phosphorus (DIP) accounted for between 6 and 19% of TP concentrations. TN:TP molar ratios ranged from 8.9 to 13.9, while DIN:DIP molar ratios ranged from 8.1 to 65.

Table 2 Water quality over the 6-month period prior to the benthic surveys (means and standard deviation) of fortnightly samples). GV guideline value included where available (ANZECC 2000)

Parameter	Units	Narrabeen	Dee Why	Curl Curl	Manly	GV
Temp	(°C)	25.1 (2.2)	24.0 (3.2)	25.2 (3.2)	25.7 (2.2)	
pH		8.0 (0.1)	7.9 (0.2)	7.8 (0.2)	7.7 (0.2)	7–8.5
Salinity		33.5 (3.6)	22.5 (6.3)	16.7 (7.6)	24.9 (6.6)	
Turbidity	(NTU)	5.7 (3.3)	3.2 (4.0)	4.4 (3.3)	4.9 (2.9)	0.5–10
fDOM	(RFU)	6.9 (2.4)	14.3 (7.0)	17.6 (3.5)	10.3 (4.0)	
Dissolved oxygen	(% sat.)	94.5 (6.8)	91.4 (16.9)	87.4 (16.5)	61.0 (18.8)	80–110
Chl- <i>a</i>	(mgL ⁻¹)	7.2 (3.3)	4.8 (5.7)	6.1 (5.2)	13.1 (6.3)	4
benthic:pelagic Chl- <i>a</i>		5.9	28.6	67.9	18.4	
NH ₄ ⁺	(mgL ⁻¹)	21.2 (27.1)	51.3 (49.1)	177.9 (164.4)	24.1 (32.1)	15
NO _x	(mgL ⁻¹)	13.3 (21.7)	43.6 (105.7)	58.6 (41.5)	34.1 (63.6)	15
DON	(mgL ⁻¹)	576.5 (335.6)	756.2 (272.1)	694.1 (139.7)	671.5 (232.8)	
TDN	(mgL ⁻¹)	387.2 (187.2)	635.7 (167.3)	744.8 (251.5)	415.1 (153.3)	
DIP	(mgL ⁻¹)	1.9 (5.9)	7.0 (13.8)	1.6 (1.9)	4.4 (8.2)	
DOP	(mgL ⁻¹)	29.0 (13.8)	30.4 (22.9)	28.6 (18.0)	42 (15.3)	
TDP	(mgL ⁻¹)	21.0 (12.3)	26.2 (20.7)	14.1 (14.6)	32.2 (17.4)	
TN	(mgL ⁻¹)	610.9 (358.5)	850.9 (282.9)	930.6 (287.3)	730.7 (262.7)	300
TP	(mgL ⁻¹)	31.0 (14.4)	37.4 (29.4)	30.2 (18.8)	46.5 (15.5)	30
DIN:DIP	molar	8.1	6.1	65.0	5.9	
TN:TP	molar	8.9	10.3	13.9	7.1	

Sediment Properties

Sediment silt content (<63 μm) tended to increase with distance upstream from the entrance in Manly (Lagoon:Site, $p < 0.0001$) and Narrabeen Lagoons (Lagoon:Site, $p < 0.0001$) (Supplementary Table S2). In Manly, site 1 was ~3 times lower than sites 2, 4 and 5 (Supplementary Table S1). In Narrabeen, silt content was ~4 times lower at sites 1 and 2 than sites 4 and 5 (Supplementary Table S1). Silt content was lowest in Curl Curl and Dee Why Lagoons with no increase in sediment silt content past site 3 in Curl Curl and no spatial trends in Dee Why (Supplementary Table S1). Sediment total organic carbon (TOC), nitrogen, chlorophyll-*a* and pheophytin concentrations also tended to increase with distance upstream from the lagoon entrances, peaking at site 4 or 5 in each lagoon (Supplementary Table S2, Fig. 2, Supplementary Table S1), and were often up to 3 times higher in Manly and Curl Curl Lagoons compared to the other lagoons (Supplementary Table S1). The strength and slope of the relationship between TOC

and sediment silt content were distinctly different among lagoons, with lower ratios in Narrabeen compared to Manly Lagoon, and the highest ratios in Dee Why and Curl Curl Lagoons (Fig. 3). Similarly, sediment chlorophyll-*a* + pheophytin and TOC were positively correlated in all lagoons, with the strength of the relationship decreasing from Narrabeen > Dee Why > Curl Curl > Manly (Fig. 3).

Benthic Metabolism

Benthic community respiration rates (CR = dark O₂ flux) were up to 6 times lower in Narrabeen Lagoon compared to Manly lagoons and varied with distance from the lagoon entrance (Lagoon:Site, $p < 0.0001$, Fig. 4, Supplementary Table S3). The highest rates were recorded in the upper sites of Manly Lagoon (sites 4 and 5, Supplementary Table S1). CR tended to decrease at the uppermost sites (site 5) of all lagoons relative to their neighbouring downstream site (site 4), which matched patterns in sediment characteristics (Fig. 2). Gross primary productivity rates

Fig. 2 Mean (± standard error) of sediment properties (at the five study sites within each of the ICOLLs. Sites are ordered (1–5) according to their distance from the entrance

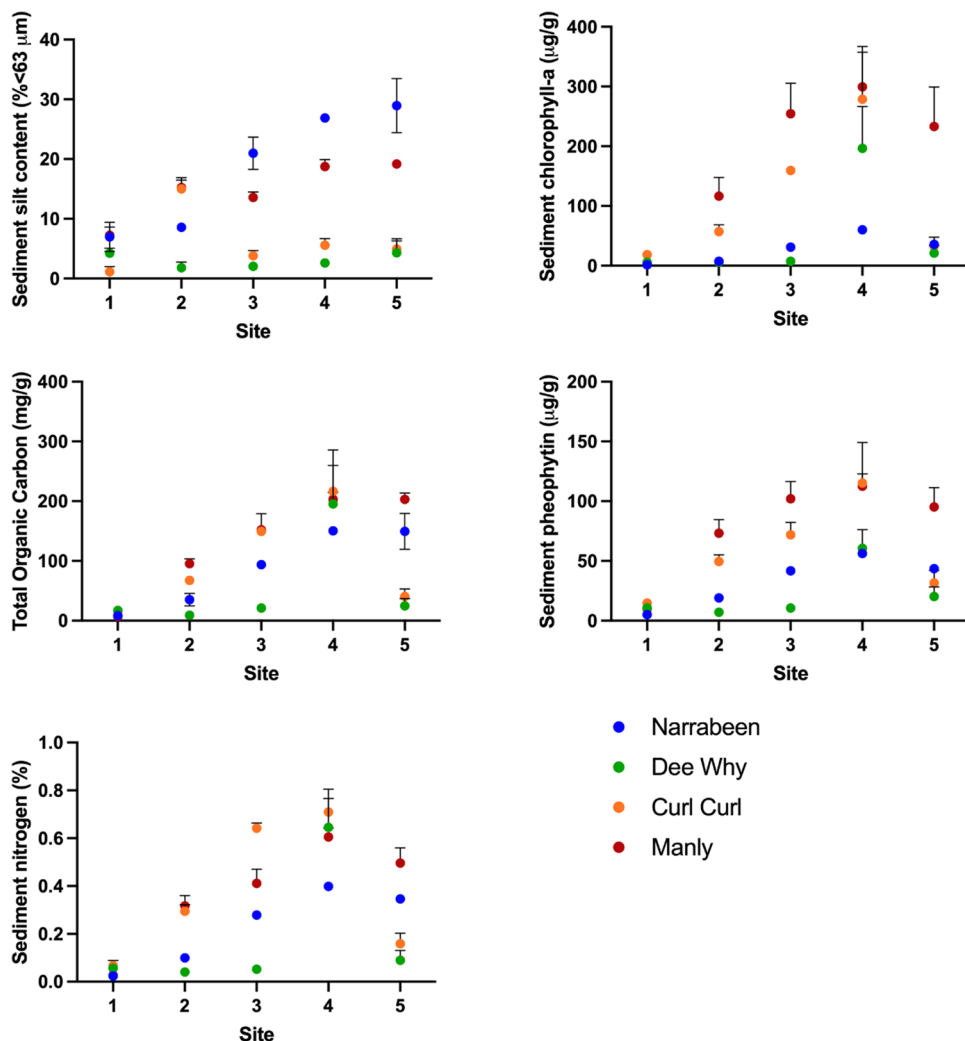
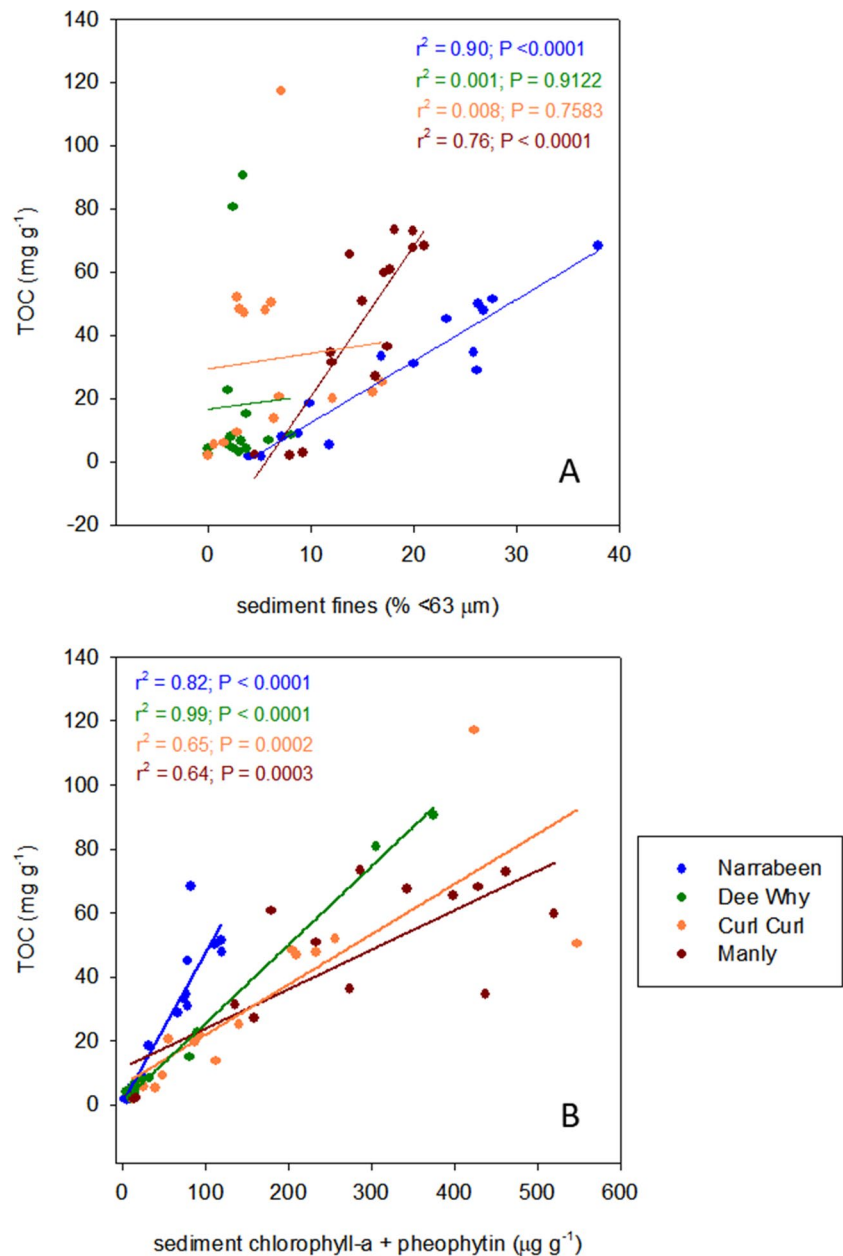


Fig. 3 The relationships between (A) sediment silt content and total organic carbon in the surface sediments; and (B) sediment chlorophylls and total organic carbon

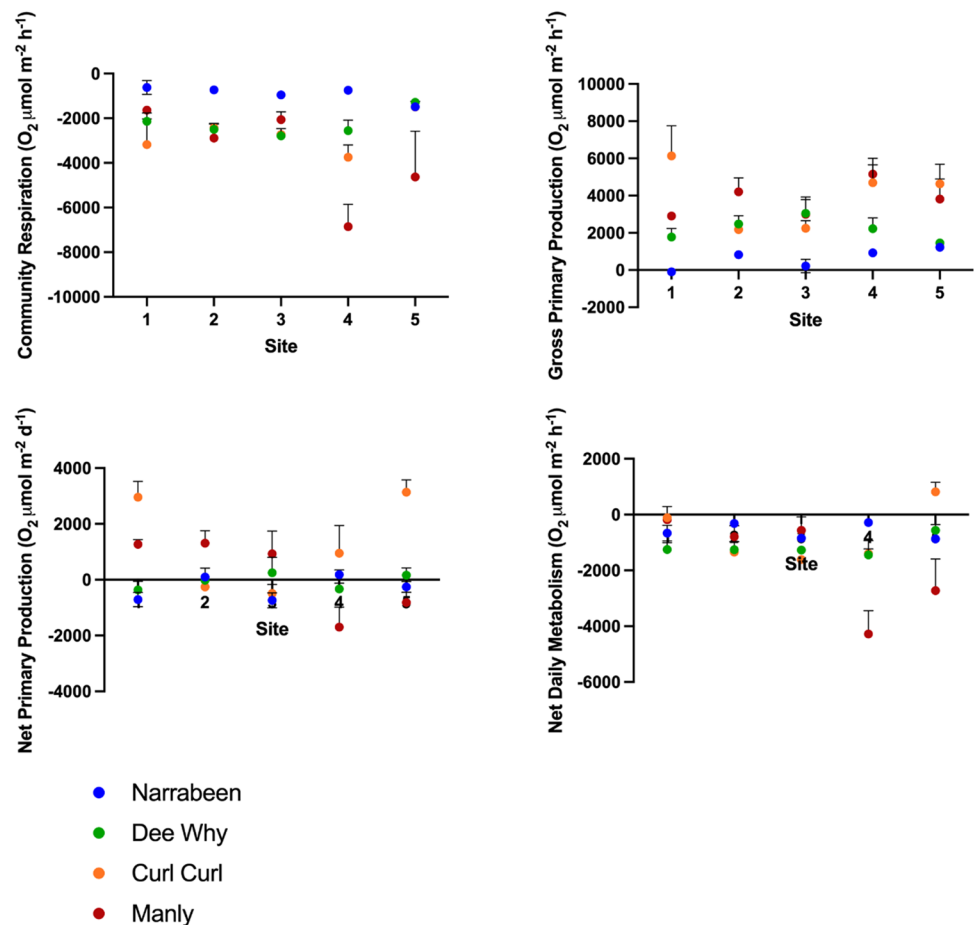


(GPP) were highest in Manly and Curl Curl Lagoons and up to 6 times lower in Narrabeen Lagoon relative to the other lagoons (Lagoon, $p < 0.0001$, Fig. 4, Supplementary Table S3). Curl Curl and Manly were the only Lagoons to differ in net primary productivity (NPP) with distance from the lagoon entrance (Lagoon:Site, $p < 0.0001$, Fig. 4, Supplementary Table S3). In Manly, sites 1, 2 and 3 were similar and NPP rates shifted from positive to negative at sites 4 and 5 (Supplementary Table S1). In Curl Curl, sites 1 and 5 were NPP rates more similar and almost double NPP rates at sites 2 and 3 (Supplementary Table S1). There were no significant spatial trends in NPP in Dee Why or Narrabeen (Supplementary Table S1). All sediments were

net heterotrophic (NDM < 0) except for the uppermost site in Curl Curl Lagoon (Fig. 4).

The relationships between sediment TOC and CR were negative for all lagoons (i.e. increasing oxygen consumption with TOC) with the strength of the relationship varying for each lagoon (Fig. 5), suggesting different contributions of labile and refractory organic matter (OM). Using sediment chlorophyll-*a* as a proxy for labile OM, the relative influence of this pool can be assessed using the Chl-*a*:TOC ratio which was positively correlated to CR ($r^2 = 0.45$, $p = 0.01$), but was still variable among lagoons (Fig. 5). The diagenesis model shows that TOC:CR observed in Narrabeen Lagoon can be accounted for by a dominance of refractory OM (~99%),

Fig. 4 Mean (\pm standard error) of benthic metabolism at the five study sites within each of the ICOLs. Sites are ordered (1–5) according to their distance from the entrance



while in Manly and Curl Curl Lagoons, the model predicts the upper limits of labile OM contributions to be $\sim 90\%$ (Fig. 5). Further, the relative proportion of labile OM in sediments across the study lagoons (as implied by the different TOC:CR for each lagoon shown in Fig. 5) increases with nutrient loading rates (Table 1), which is consistent with the observed variation in Chl-*a*:TOC values (Fig. 3A).

Relationships Between Morphometrics, Water Quality, Sediment Properties and Benthic Metabolism

The principal components analysis (PCA) revealed three components that described 76.6% of variation in the input data (Fig. 6, Supplementary Table S5). PC1 explained 36.7% and PC2 explained 29.3% of the variation. The observations are clearly differentiated along the two axes: (1) a morphology gradient (waterway area, mean depth and the percentages of area less than 1 m deep and below mean sea level); and (2) nutrient loadings. Sediment silt contents and some water quality parameters are clearly related to morphology, while benthic processes (benthic community respiration and gross primary productivity) are closely associated

with nutrient (nitrogen and phosphorus loading). The study ICOLs are grouped according to the deeper lagoons (Manly and Narrabeen) and shallower lagoons (Dee Why and Curl Curl), with clear separation according to nutrient loading between the deeper lagoons and a lesser separation between the shallower lagoons. There is also evidence of within lagoon variation along the nutrient loading gradient (e.g. Manly Lagoon).

Discussion

We investigated how physical forcings such as hydrology and morphology interact with catchment nutrient inputs to influence indicators of eutrophication in coastal lagoons. We found distinct patterns in lagoon morphometrics, water quality, sediment properties and benthic metabolism across the four studied systems, with benthic processes such as community respiration more closely linked to nutrient loading than traditional water quality indicators such as chlorophyll-*a*. Manly and Narrabeen are linear, deeper systems that showed variation in sediment properties with distance from the entrance. However, evidence of eutrophication was only

Fig. 5 The relationships between (A) total organic carbon (TOC) and benthic community respiration (CR); (B) the sediment chlorophyll-*a*:TOC ratio and CR. (C) Comparison of measured TOC:CR with the diagenesis model for refractory and labile dominated TOC pools

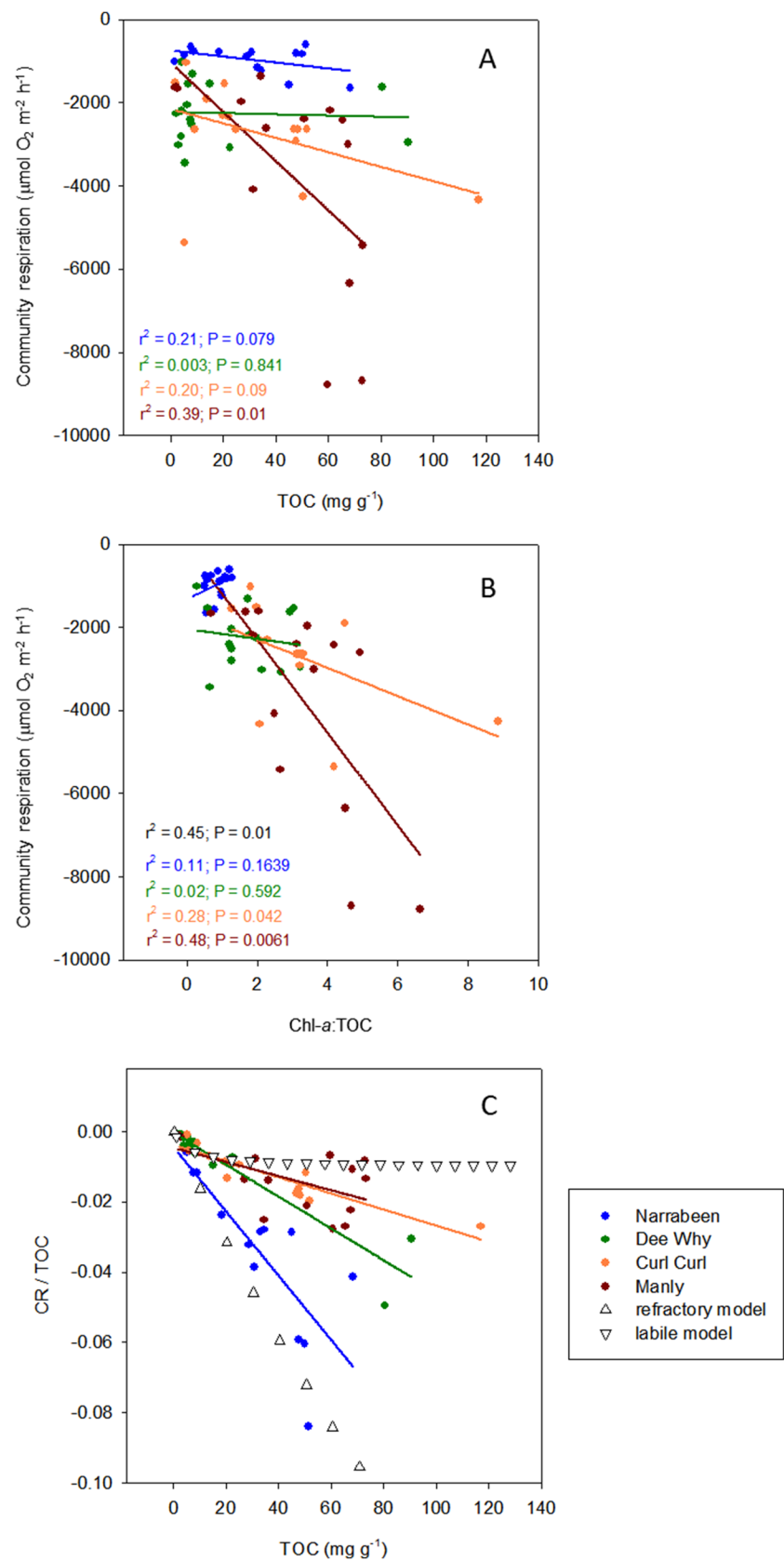
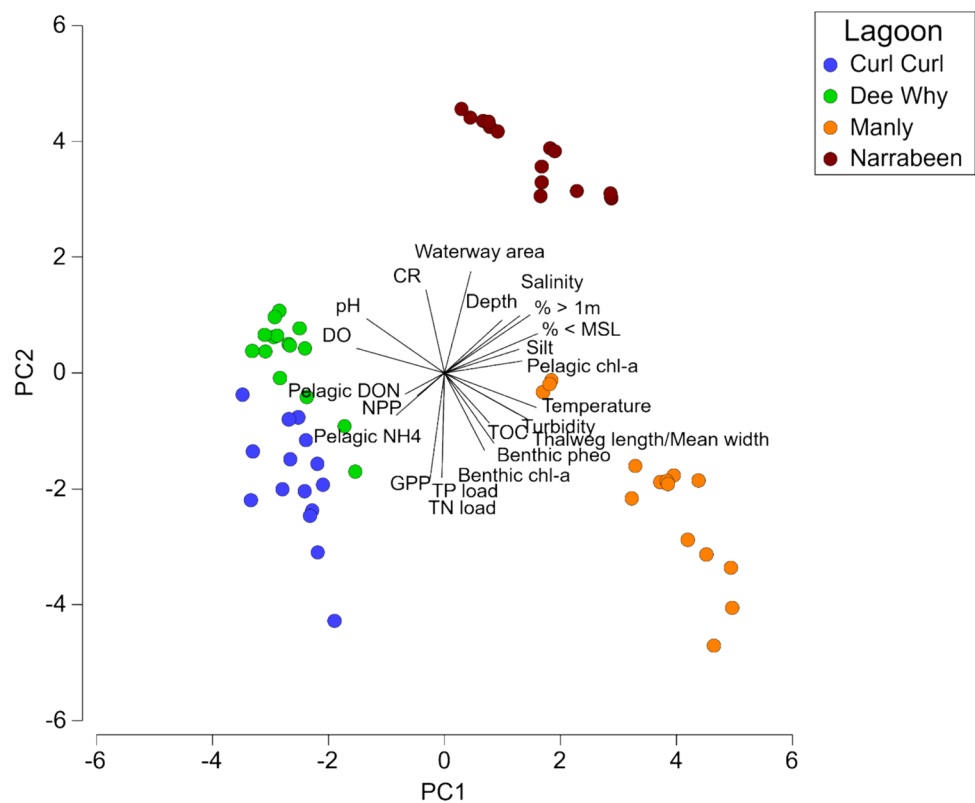


Fig. 6 Principal components analysis (PCA) describing broad trends among the study systems and relationships between morphology, nutrient loading, water quality, sediment properties and benthic processes. Morphological parameters included waterway area, depth, thalweg length/mean width, area below mean sea level (MSL) and area deeper than 1 m. Nutrient loading parameters included total phosphorus and total nitrogen loads standardised to volume. Water quality parameters included temperature, salinity, dissolved oxygen, pH, turbidity, pelagic chlorophyll-*a*, pelagic dissolved organic nitrogen and pelagic ammonium. Benthic process parameters included community respiration, gross primary productivity and net primary productivity. Sediment properties included benthic chlorophyll-*a*, benthic pheophytin, total organic carbon and silt content



observed in Manly where total organic carbon, nitrogen and sediment chlorophyll-*a* were up to 3 times higher than Narrabeen or Dee Why and the diagenesis model found dominance of labile organic matter linked to increasing nutrient loading. These findings suggest that lagoon morphometry and nutrient dynamics are critical determinants of benthic processes, with implications for assessing eutrophication and managing these important coastal systems.

Estimated nitrogen (N) and phosphorus (P) loadings to our study lagoons span the reported range for shallow coastal bays (Derolez et al. 2019; McGlathery et al. 2007) suggesting that our study should provide a reasonable indication of loading pressure and response in these ICOLLs. However, nutrient loading and water quality indicators were not always strongly correlated even though nutrient and chlorophyll-*a* concentrations were often elevated over the Australian and New Zealand water quality guideline values for the protection of aquatic ecosystems (ANZECC 2000) in all lagoons. In contrast, rates of benthic community respiration (CR) were positively correlated with volume-normalised nutrient loadings (Fig. 6), with some sites in Curl Curl and Manly Lagoons falling in the eutrophic to hypertrophic range (Fig. 4), where denitrification efficiency has been shown to be reduced to below 30% (Eyre and Ferguson 2009). This is an important indicator of eutrophication since denitrification contributes to the removal of excess nitrogen from estuarine systems and reduced denitrification

efficiency can lead to accumulation of nutrients triggering algal blooms and other associated impacts (Crawshaw et al. 2019). Further, benthic oxygen fluxes measured in this study reflect aerobic pathways and so may underestimate mineralisation by anaerobic pathways. Therefore, actual rates of total organic carbon breakdown are likely higher (Blackburn 1988; Jørgensen 1982). This suggests that water quality alone may not be a robust indicator of ecosystem health in these systems and that a consideration of benthic processes is critical (Fellows et al. 2006). However, the organic enrichment of sediments suggested by the high rates of benthic CR at some of our study sites is not clearly borne out by simple relationships with measures of organic matter, requiring a more nuanced model that includes interactions among nutrient loading, hydrological and morphological factors to describe the ecosystem functions and eutrophication in these ICOLL systems.

Influence of Morphometrics and Hydrodynamics

Benthic CR is driven by two principal factors: the quantity and quality of sediment organic matter, which in turn is controlled by the relative supply of allochthonous and autochthonous inputs. The supply of inputs is mediated by factors such as morphology and hydrodynamics that affect material deposition and scouring (i.e. net accumulation; (Glud 2008; Grant and Hargrave 1987; Hossain et al. 2003; Liu

et al. 2015). The PCA (Fig. 6) indicated that sediment silt content and some water quality parameters across the study systems were closely associated with morphology (particularly depth), which is consistent with a net accumulation of finer material (e.g. silts, clays and phyto-detritus) in deeper, lower energy environments (Roy et al. 2001). Similarly, sediment silt content increased with water depth at a site level, moving upstream from the higher energy environment of the marine delta shoals to the central mud basins of the deeper systems (i.e. Manly and Narrabeen Lagoons; Fig. 2); however, these trends were not apparent in the shallower systems (Dee Why and Curl Curl Lagoons; Fig. 2). We propose that these discrepancies can be explained by considering some unique interactions between morphology and hydrodynamics as discussed below.

The flocculation and deposition of material laden water, that enters the lagoon from upstream, depend on the physical characteristics of the lagoons. It was hypothesised that lagoons with a more linear shape (more mature) would accumulate external inputs in the upper and middle reaches due to fresher water from storm drains mixing with saltwater. In contrast, in lagoons with a more circular shape (less mature), these inputs are distributed more homogeneously throughout the body of the lagoon through wind-driven currents (Haines et al. 2006). For this reason, we expected more sediment enrichment in sites further from the mouth in Manly and Curl Curl lagoons, which are classified as linear systems (displacement-dominated lagoon) by Haines et al. (2006). We observed that sediment enrichment increased with increasing distance up to the fourth sampling site with a subsequent decrease at the innermost site not only in Curl Curl and Manly lagoons, but also in Narrabeen (classified as mixing-dominated lagoon; Haines et al. 2006). Although Narrabeen has a circular shape, this lagoon has a larger waterway area and depth, which can limit drainage of the lagoon at upstream sites, making these hotspots for the accumulation of organic matter. In contrast, Dee Why (which is also classified as mixing-dominated lagoon, but with a smaller size and depth) may be able to drain completely when opened to the ocean, resulting in the more constant concentration of TOC, TN and benthic Chl-*a* observed along its length.

Periodic closure of the ocean entrance is a key feature of ICOLLs, allowing catchment inputs (freshwater, sediments and pollutants) to accumulate in the system until entrance breakout occurs (Suara et al. 2018; Warwick et al. 2018). All four systems in this study are actively managed with Dee Why, Narrabeen and Curl Curl Lagoons artificially opened at predefined water level thresholds to alleviate flooding in fringing urban areas, while Manly Lagoon is effectively permanently open via a concrete culvert across the entrance berm. During closed entrance conditions, tidal energy is absent and so bed shear stress is determined by exposure

to wind-wave energy, which may be expected to be greater in shallower systems with a lower thalweg:width ratio (e.g. Dee Why and Curl Curl). During our sampling period, all lagoons were closed apart from Manly Lagoon. Wind-wave energy and resulting currents in these systems would tend to break down the expected spatial patterns of material accumulation along the thalweg (de Vicente et al. 2010; Kjerfve and Magill 1989).

The trapping of material during closed entrance conditions is subsequently offset when entrance breakout occurs and the system drains, exporting a potentially large percentage of the water column and potentially scouring material from shallow sediments (Haines 2006; Mayjor et al. 2023). Sediment scour is likely to be greatest across entrance shoals where water velocities are highest, but still may occur across shallow sediments upstream (Gale et al. 2006; Haines 2006; Suara et al. 2018). Although not measured during this study, observations in nearby ICOLLs show significant increases in turbidity occurring as ICOLLs drain suggest the mobilisation of fine sediment material from shallower areas further upstream (Ferguson unpublished data and see Maher et al. 2011). This ‘cleansing’ effect is likely greater where the system drains completely, and may account for the significantly lower sediment silt content in Dee Why and Curl Curl Lagoons. In contrast, there is potential for the net retention of material where a deeper basin extends below mean sea level such as in Narrabeen and Manly Lagoons.

Deeper systems with higher nutrient inputs tend to have sediments with more autochthonous organic matter than sand-dominated systems. In general, it is expected that sediment organic matter (OM) within a system will be highest in depositional environments (Pickett 1984; Roy et al. 1980). Accordingly, there were positive relationships between sediment silt content and OM observed during this study; however, the slope of this relationship was not consistent among systems (Fig. 3A). In the deeper systems (that do not drain completely after entrance breakout), OM and sediment silt content distributions were similar, with a higher slope for the total organic carbon (TOC):silt relationship in Manly Lagoon (Fig. 3A) relative to Narrabeen Lagoon where TOC was more closely related to sediment chlorophyll-*a* content (Fig. 3B). This stronger relationship between TOC and silt in Manly Lagoon is most likely explained by greater autochthonous production of organic matter (e.g. phytoplankton and benthic microalgae) due to much higher nutrient loading rates in Manly Lagoon. In contrast, the accumulation of benthic OM in the sand-dominated shoals of the shallow systems appeared to be uncoupled to the dynamics of silty sediments which are potentially minimised by scouring during entrance breakout. TOC:silt in these systems increased with decreasing depth, most likely reflecting a dominance of microalgal mats whose influence on the cohesion of surface sediments

may help to resist scouring upon entrance breakout (Madsen et al. 1993; Pan et al. 2019).

Relationships Between Benthic OM and Metabolism

Our study has described some key morphological controls over the accumulation of sediment OM in ICOLLs which are independent of nutrient loading. Nonetheless, nutrient loads are likely to influence benthic CR insofar as they affect the autochthonous production of OM. The significantly different slopes for TOC:CR across the study systems all fall within the bounds of the refractory and labile model and clearly point to different relative contributions of refractory and labile OM to TOC (Fig. 5). The increase in labile OM (Fig. 5C) and Chl-*a*:TOC with increasing nitrogen loading rates is consistent with the stimulation of algal growth expected for eutrophication (Cloern 2001). Hence, it appears that despite morphological controls over OM distribution, eutrophication in these systems is primarily expressed as an increase in the relative contribution of labile OM in sediments and concomitant stimulation of benthic metabolism.

The dominance of benthic chlorophyll-*a* over pelagic chlorophyll-*a* across our study systems (as indicated by benthic:pelagic Chl-*a*; Table 2) highlights the importance of benthic processes in these systems. While we cannot discount a potential contribution of phyto-detritus to sediment chlorophyll-*a* (and therefore OM), the high rates of benthic gross primary productivity (GPP) and a strong relationship between benthic:pelagic chlorophyll-*a* ratios and system morphology suggest benthic microalgae productivity is a dominant OM source (Fig. 6). The relative contribution of algal material to sediment OM (as indicated by Chl-*a*:TOC; Fig. 3B) increased with GPP, while benthic GPP increased with nutrient loading at a system level (Fig. 6). The stimulation of benthic microalgae (BMA) productivity and biomass has been demonstrated experimentally (Sundbäck and Snoeijs 1991; Tsikopoulou et al. 2020) and BMA are known as a temporary nutrient sink in shallow systems which can help buffer against eutrophication (Gil-Izquierdo et al. 2021; Sundbäck and McGlathery 2005). However, the generalised conceptual model of eutrophication in coastal systems describes a reduction in benthic productivity at the expense of increased pelagic productivity in response to nutrient inputs, leading to shading from increased pelagic algal biomass that shades the BMA and an eventual state-shift whereby benthic productivity eventually collapses (Cloern 2001; Krause-Jensen et al. 2012). Our results suggest a different and paradoxical paradigm: while BMA in shallow ICOLLs may play an important role in buffering against eutrophication of the water column, it may also contribute to organic enrichment of sediments. A potentially important aspect to the maintenance of this role is

the scouring effect of periodic breakout events whereby the system is ‘reset’ and some pelagic and epibenthic OM is exported from the system. In deeper systems with a depositional basin, BMA biomass still significantly contributes to OM but against a much larger background of allochthonous material.

Conclusion

Our study surveyed water quality, sediment quality and benthic metabolism in four shallow ICOLLs that experience a wide range of nutrient loadings. Despite nutrient loading rates for two of the ICOLLs being at the upper end of the reported global range, nutrient loading was weakly correlated to traditional water quality indicators of eutrophication. In contrast, benthic community respiration was closely correlated with nutrient loading rates across the study systems, suggesting that benthic processes are a critical indicator of eutrophication in these shallow systems. However, the expression of eutrophication appears to be nuanced by interactions between morphology and hydrodynamics, which control the ratio of pelagic to benthic production and net accumulation of sediment organic matter with distance from the lagoon entrance. Organic matter can accumulate during closed entrance conditions, while scouring and export can occur during entrance breakout events thereby ‘resetting’ the system. However, the effectiveness of this ‘reset’ is dependent on the depth of the system and to what extent its basin extends below mean sea level.

We provide a conceptual model of nutrient and organic matter cycles in ICOLLs where: (A) the central basin is perched above mean sea level, and (B) the central basin extends below mean sea level (Fig. 7). In the first case (A), light penetrates to the sediments and benthic microalgae compete for available nutrients resulting in high rates of benthic primary productivity and a relatively high biomass of benthic microalgae (as indicated by the benthic:pelagic chlorophyll-*a* ratio). This pathway dominates the response of the system to excess nutrient inputs, buffering it against the typical expression of eutrophication. In the second case (B), the deeper central basin tends to accumulate fine sediments and organic matter, and the benthos is more light limited. This leads to a relative dominance of phytoplankton productivity and biomass. Benthic community respiration is driven by (1) the quality (labile vs refractory); and (2) the quantity of sediment organic matter, and is proposed as a more sensitive indicator of nutrient enrichment and eutrophication in these ICOLL systems compared to more traditional water quality indicators. Periodic entrance breakout results in the export of material due to the potential fine sediment and organic matter scour across shallower shoals which may serve to ameliorate the impacts of eutrophication.

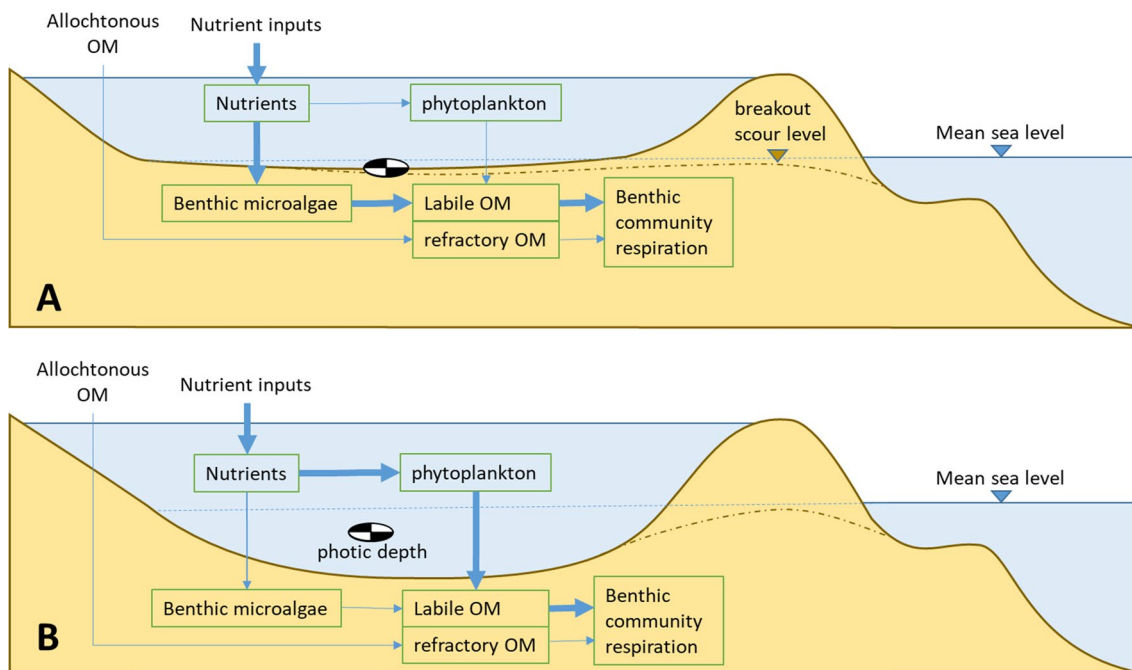


Fig. 7 Conceptual model of nutrient and organic matter cycles in ICOLLs where (A) the central basin is perched above mean sea level, and (B) the central basin extends below mean sea level

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12237-024-01430-y>.

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Data availability Data will be made available on request.

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