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Nitrogen Budget for Cockburn Sound, Western Australia

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Executive Summary

A nitrogen budget for Cockburn Sound is presented for the purposes of understanding the importance of the various sources of nitrogen and how they are used for primary production in order to inform assessment of the health of the Cockburn Sound ecosystem and how this has responded to reduced anthropogenic nitrogen inputs and improved water quality over the last 30 years.

Sea grass coverage in Cockburn Sound is currently 748 hectares which is about 20% of the area of the Sound less than 10 m deep. In 1967 this same area had 80% coverage of seagrass. As a consequence, seagrass now comprises only 3% of the demand for nitrogen for photosynthesis in Cockburn Sound with phytoplankton responsible for 91% of all nitrogen uptake for primary production. We found that SGD inputs represent between 13% and 27% of the total nitrogen used by photosynthetic plants in Cockburn Sound (depending on whether the upper or lower limit of SGD nitrogen input is adopted), with the remainder being supported by recycled nutrients. Overall, this suggests that Cockburn Sound is primarily a recycling system, with a small relative contribution from groundwater nitrogen. Such reliance on recycled nitrogen may help to explain why chlorophyll biomass in Cockburn Sound has been slow to respond to reductions in external SGD nitrogen load, and suggests that the pelagic ecosystem will be more sensitive to changes in recycling efficiency either within the water-column or sediment, than it would to relatively small proportional changes in the external supply.

Managed aquifer recharge (MAR), the infiltration of treated wastewater to the Superficial Aquifer has been proposed for the Kwinana Industrial Area adjacent to the Sound as a source of non-potable water for heavy industry, horticulture and local government and to help wetlands recover from the impacts of drying climate. The relative contribution of submarine groundwater discharge (SGD) to the nitrogen budget of Cockburn Sound needs to be known in order to determine any possible impacts of MAR on the ecosystem. If the additional nitrogen and water fluxes to the Sound were significant, further treatment prior to infiltration of the MAR water to remove nitrogen may be required, which would increase costs and reduce the viability of water reuse for industry. An earlier study showed that the amount of SGD varies greatly between dry and wet years and is expected to reduce below current levels, with or without MAR, because of a drying climate and continued reduction in groundwater levels. Along with a substantial reduction in point source pollution, the reduction of SGD may partially explain the reduction in total nitrogen in the water column in Cockburn Sound in recent decades.

The possible addition of nitrogen, as a result of Managed Aquifer Recharge (MAR), estimated to be up to a maximum of ~185 t N y^{-1} (Donn et al., 2015), would only increase the SGD contribution to ~20% for the lower limit of SGD, and 34% for the upper limit which is still a relatively minor term in the overall budget. According to the proposed budget (Figs. 5 and 6), an increase in SGD supply would either be balanced by a reduced reliance on recycled N (shift to higher *f*-ratio), or alternatively lead to enhanced plant productivity. In either case, an increase in seabed deposition would result, demanding an increase in the burial/denitrification flux in order for the N budget to stay in balance.

Given the importance of resolving questions about the risks posed by small amounts of additional nitrogen inputs to Cockburn Sound from MAR, we recommend a set of key measurements be made to reduce the uncertainties in the nitrogen budget presented here. These are to undertake new measurements of groundwater nutrient concentrations along the eastern Cockburn Sound shoreline (current data are 15 years old) and undertake direct measurements of phytoplankton productivity, rates of sediment denitrification and sediment nutrient fluxes in Cockburn Sound.

1 Introduction

Primary productivity on the West Australian (WA) continental shelf is primarily limited by availability of dissolved nitrogen (Koslow et al., 2008; Thompson et al., 2011) which is usually scarce resulting in low productivity and optically clear waters. Against these low-nutrient background conditions, the anthropogenic addition of nitrogen can elicit a strong biological response, leading to algal blooms and changes in water clarity. This is evidenced by changes in Cockburn Sound during the 1970's when anthropogenic additions of nitrogen went unchecked. Subsequent measures to control nitrogen inputs to the Sound have effectively reduced the total in-water nitrogen concentration to low levels (Keesing et al., 2016). However, phytoplankton biomass (inferred from the in-water concentration of chlorophyll pigment) has been slow to respond, and still remains high at some monitoring sites (Keesing et al. 2016). Several reasons for this slow response have been discussed previously (CSMC, 2001), but the matter has not been resolved. Equally, despite improved water clarity, seagrass recovery has been poor. Seagrass health indices have also declined at the reference location, Warnbro Sound (Mohring and Rule 2013), so may be the result of factors other than nitrogen or water clarity. Managed aquifer recharge (MAR) has been proposed for the Kwinana Industrial Area adjacent to the Sound as a source of non-potable water for heavy industry, horticulture and local government and to help wetlands recover from the impacts of drying climate. However, any plans to implement MAR need to address concerns that additional inputs of nitrogen could hinder the continued recovery of the Cockburn Sound ecosystem (McFarlane 2015). Balancing this concern is that, if well managed, added nitrogen may be intercepted by industrial groundwater extraction. The effect of further drying of the catching also appears to more than offset any added water and nitrogen (Donn et al. 2015). To help inform and understand the risks associated with potential nitrogen additions to the Sound as a result of MAR, we have constructed a nitrogen budget. The purpose of the exercise is not to predict how the system might respond to additions of nitrogen, but rather to identify the critical nitrogen pathways, and in particular assess the relative contemporary importance of groundwater nitrogen inputs versus internal nitrogen cycling.

An earlier nitrogen budget (CSMC, 2001) representing conditions in the Sound in the year 1978, suggested that inputs at that time were in excess of water-column demand by 160 t N y^{-1} (Fig. 1a). This nitrogen excess is consistent with high concentrations of dissolved nitrogen in the water-column during the 1970's (Keesing et al. 2016). In contrast, a nitrogen budget for conditions in 2000 (CSMC, 2001) revealed an apparent deficit of at least 550 t N y^{-1} (Fig. 1b). This arose because external inputs (via submarine groundwater discharge (SGD), runoff and atmospheric fixation) estimated to be 300 t N y^{-1} (~ 7 times lower than had been estimated for 1978), plus internal in-sediment recycling, estimated at a maximum rate of 1950 t N y^{-1}, were insufficient to meet the combined demand from phytoplankton and epibenthic microalgae, estimated to be 2790 t N y^{-1} (Fig. 1b). The imbalance appears even worse if productivity from seagrass is included, estimated here to be at least 60 t N y^{-1} based on 1999 coverage maps (Kendrick et al. 2002) and nitrogen demand (Cambridge and Hocking, 1997), or the minimum suggested sediment flux of 970 t N y^{-1} is applied instead of the maximum. In the most extreme case the deficit might have been in excess of 1500 t N y^{-1}. The reason for this budget imbalance is uncertain but previous nitrogen accounting for the WA continental shelf suggests that approximately half of the primary productivity (pelagic plus epibenthic) at this scale is supported by highly efficient water-column recycling (Feng & Wild-Allen, 2010).

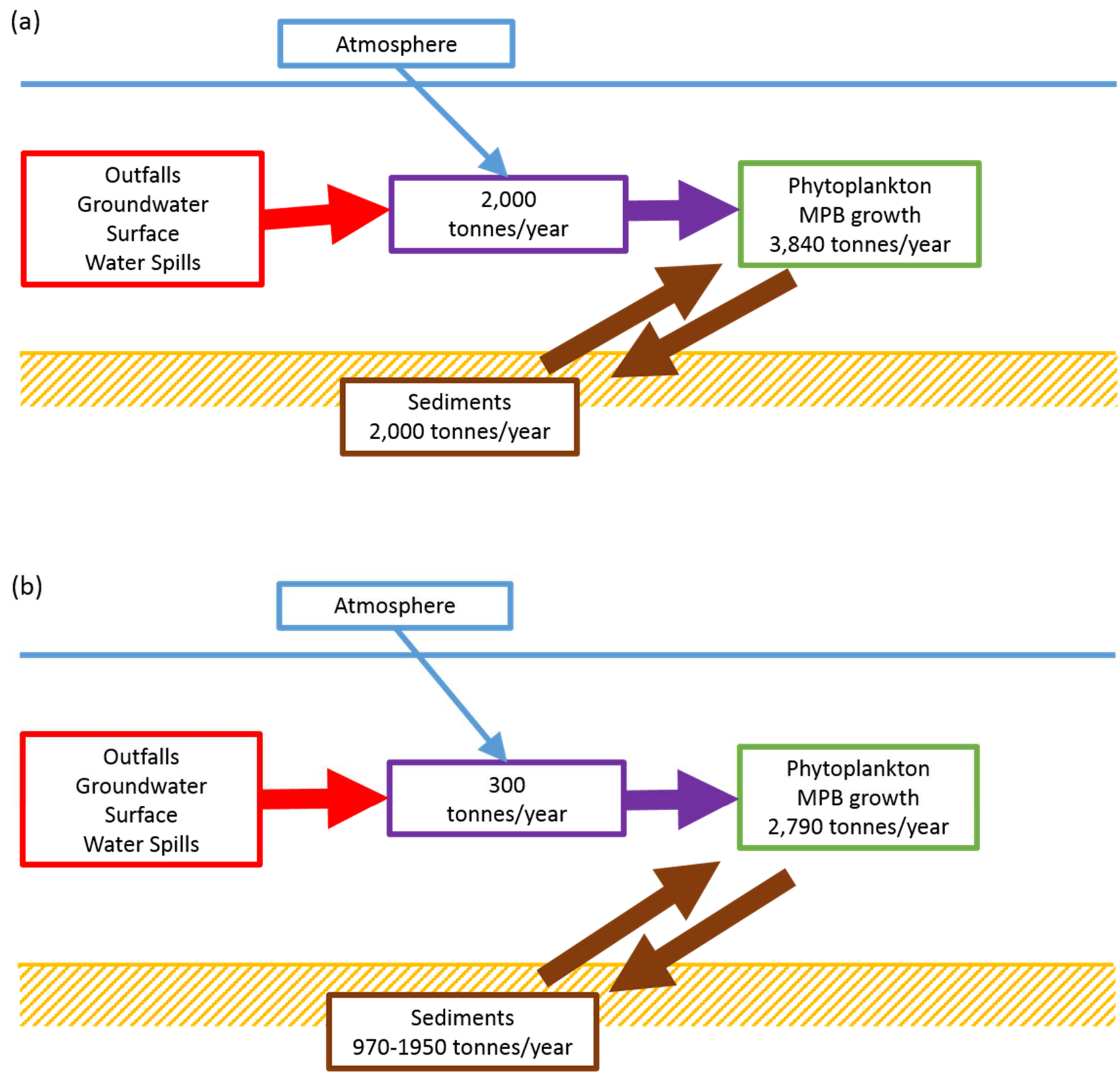

Figure 1. Estimated nitrogen inputs from sediment and human activities and amount of nitrogen required by phytoplankton and epibenthic microalgae (also referred to as microphyto benthos (MPB)) in (a) 1978 and (b) 2000. Reproduced from CSMC 2001.

In this paper, we present a more detailed budget that uses updated estimates of groundwater nitrogen input (Donn et al. 2015), explicitly includes nitrogen recycling, and considers losses of nitrogen at the seabed and via exchange with the shelf.

2 Nitrogen budget

Our nitrogen budget is applied to a region of Cockburn Sound defined by the WA mainland and Garden Island coastline, the Garden Island causeway (between Garden Island and Cape Peron), and an open boundary between the northern tip of Garden Island and Woodman Point (Fig. 2). For estimates of phytoplankton and epibenthic microalgae (BMA) productivity the amount of photosynthetically available radiation (PAR) at depth is calculated from an average surface solar radiation estimate obtained from the National Centre of Environmental Prediction (470 µE m^{-2} s^{-1}), and mean exponential vertical PAR attenuation rates measured during summer months between 2008-2014 (Keesing et al., 2016). For mapping purposes we use a LiDAR bathymetry data set provided by the Department of Transport, sub-sampled at 50 m resolution (Fig. 2). Our nitrogen budget includes fluxes only (not inventories) and is constrained by an assumption of mass conservation; i.e. total inputs equal total outputs.

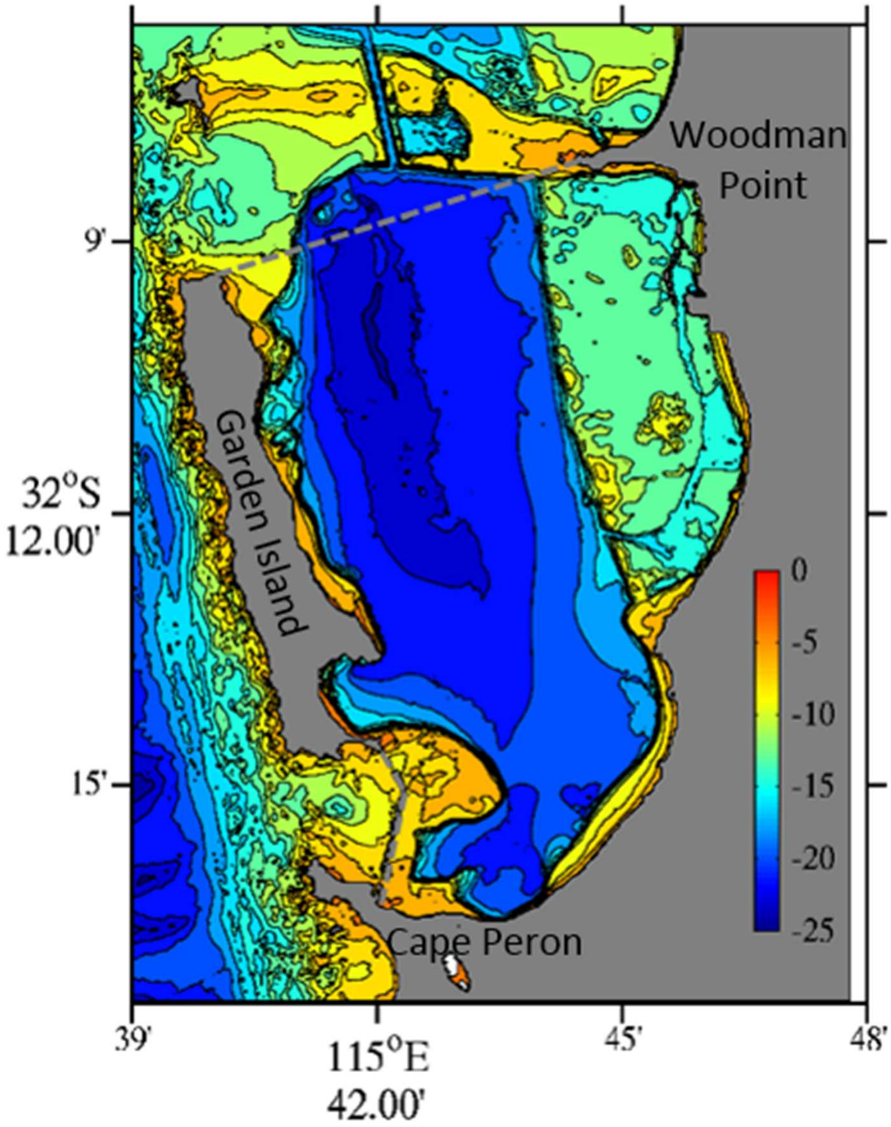

Figure 2. Measured bathymetry (m) at 50 m resolution used for mapping. The grey dotted line between Garden Island and Woodman Point marks the northern boundary of the nitrogen budget domain. The southwest boundary is defined by the causeway (grey line) between Garden Island and Cape Peron.

2.1 Inputs

2.1.1 Terrestrial

Following re-direction of urban and industrial wastewater to the Cape Peron Sepia Depression ocean outfall, the majority of the present day terrestrial nitrogen input into Cockburn Sound is accounted for by submarine groundwater discharge (SGD). Urban stormwater drains that remain in the south of the Sound are considered to represent only a very small additional nitrogen input, and are ignored in this assessment. Most recent estimates suggest that the total SGD nitrogen supply is between 450 and 920 t N y^{-1} depending on annual rainfall (Donn et al., 2015). These are considered to be over-estimates for the present day, as they rely on out-dated estimates of groundwater nitrogen concentration, as used previously by Smith et al. (2003), that are likely to have dropped in recent years (Donn et al., 2015). We compare the nitrogen balance required for both the upper and lower limit of estimated SGD input.

2.1.2 Atmosphere

Nitrogen can enter the marine ecosystem from the atmosphere via several processes including dust deposition, rainfall and biological N_2 fixation. For the purpose of this budget we reply on estimates made previously for the WA shelf (Feng & Wild-Allen, 2010). Accordingly, N_2fixation is estimated to be the largest of these with a magnitude of 7.4 t N y^{-1}, followed by rainfall at 2.1 t N y^{-1}, and a small contribution from dust of 0.4 t N y^{-1}, providing a total estimated atmospheric input of ~10 t N y^{-1} (Fig. 5).

2.2 Outputs

2.2.1 Offshore

Cockburn Sound is bounded to the east by the mainland, and to the west by Garden Island. The southern end of the Sound is almost closed by the Southern Flats, an area 1-3 m deep, and a rock-fill causeway which has two narrow openings to the sea approximately 300 and 600 m wide. To the north there is a shallow submerged sill, Parmelia Bank, which spans the full northern width of the Sound, and ranges in depth from 2 to 5 m (Fig. 2). As a consequence of the topography, exchange of water with the open sea is restricted. Flushing varies seasonally and spatially with an average volume exchange estimated to be 1.4×10^7 m^3 d^{-1} (Steedman & Craig, 1983). Concentrations of total nitrogen measured on the northern boundary (monitoring station 'CS5', Keesing et al. 2016), and averaged between 2008 and 2014 (119 µg l^{-1}), are taken to represent the open sea concentration, and are compared with average concentrations within the Sound (excluding 'CS5') during the same period (129 µg l^{-1}, Keesing et al. 2016). This yields a net loss of nitrogen of 51 t N y^{-1} (Fig. 5).

2.2.2 Seabed

A proportion of detrital matter deposited at the seafloor is expected to escape remineralisation and become buried, representing a net loss of nitrogen. Additional losses of nitrogen to the atmosphere commonly occur in marine sediments via bacterial denitrification. Sediment losses of nitrogen have been previously estimated for the WA shelf to account for ~10 % of the photosynthetic nitrogen demand in the water column (Feng & Wild-Allen, 2010). In the case of Cockburn Sound the sediment loss term (burial + denitrification) is estimated as the residual required to balance the nitrogen budget.

2.3 Biological demand

Total photosynthetic nitrogen demand (phytoplankton + seagrass + epibenthic microalgae) for Cockburn Sound is estimated here to be 3212 t N y^{-1}. This compares with a previous estimate (excluding seagrass) of 2790 t N y^{-1} (CSMC, 2001). The contribution from macroalgae is considered to be small owing to limited rocky reef habitat in the Sound, and is ignored in this budget. The possible contribution to demand by filamentous epiphytic algae growing on seagrass is also ignored. We assume it is small, given that the area of seagrass is also small in Cockburn Sound. Details of our calculation for each component are provided in the following sub-sections.

2.3.1 Phytoplankton

To our knowledge, no direct measurements of pelagic phytoplankton productivity have been made in Cockburn Sound. However, it is possible to estimate productivity (*P*) by using a photosynthesis-light relationship.

$$P = P_{sat}\left(1 - e^{\frac{-\propto.PAR}{P_{sat}}}\right) \qquad (1)$$

where P_{sat} and α are empirical fitting parameters, and *PAR* retains its earlier meaning. This approach assumes that phytoplankton growth is light limited. The value of P_{sat} and α are usually obtained from fitting equation 1 to laboratory measurements of chlorophyll normalised carbon uptake rates under controlled light conditions. We have chosen parameter values (P_{sat} = 1.0 h^{-1}; α = 0.02 mgC $mgChl^{-1}$ h^{-1} μE^{-1} m^2 s) consistent with previous ecosystem modelling for WA shelf waters (Greenwood & Soetaert, 2008). The estimates of productivity obtained in this way are then depth-integrated for Cockburn Sound (assuming that growth ceases at the 1% isolume), and multiplied by depth-averaged summertime *in-situ* chlorophyll concentration measured between 2008 and 2014 (Keesing et al 2016), and 24 hours, to yield productivity in units of mg C mg Chl*a* m^{-2} d^{-1} (Fig. 2). Rates are estimated to be highest in the southeast of the Sound and in the vicinity of Northern Harbour where chlorophyll biomass is reportedly much higher than elsewhere in the Sound (Keesing et al., 2016). Levels of productivity of ~200 mg C mg Chl*a* m^{-2} d^{-1} along the northern perimeter of the Sound (Fig. 2) are consistent with *in situ* estimates made in similar water depth further north near Two Rocks (Koslow et al., 2008) and with the average pelagic production estimated for the WA shelf (Feng & Wild-Allen, 2010). Total phytoplankton nitrogen demand for the Sound is calculated assuming Redfield nutrient ratio (C:N = 106:16) to be 2937 t N y^{-1} .

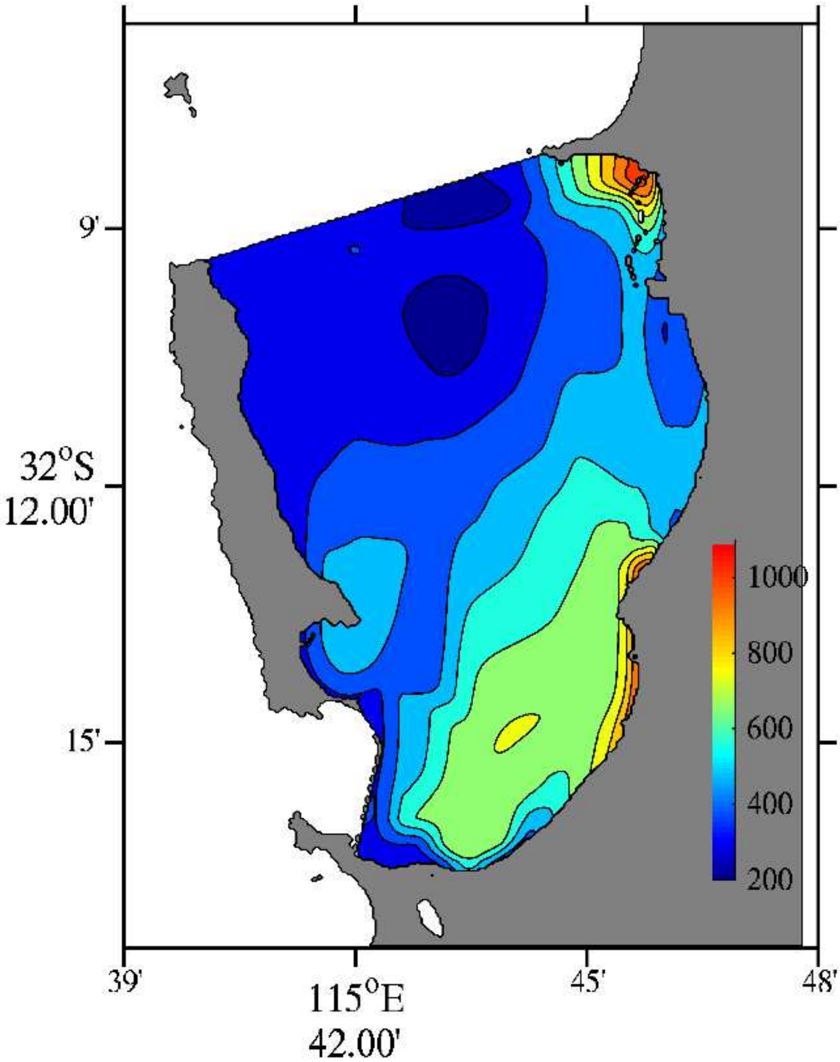

Figure 2. Estimated distribution of depth-integrated pelagic productivity (mg C mg Chl*a*$^{-1}$ m^{-2} d^{-1}). Based on mean chlorophyll *a* levels measured in the Sound between 2008 and 2014.

2.3.2 Seagrass

The productivity of seagrass is based on areal coverage estimated in a 2008 habitat data set originally prepared by BMT Oceanica for Fremantle Ports and Cockburn Sound Management Council. Here, all seagrass species (predominantly *Posidonia sinuosa* and *Posidonia australis*) are grouped together to provide total seagrass coverage at a spatial resolution of 50 m (Fig. 3). Total coverage at this resolution was calculated to be 747.5 ha, which compares with a previous estimate of 661 ha based on 1999 coverage maps (Kendrick et al., 2002). Seagrass coverage (Fig. 3) was combined with estimates of nitrogen demand for *P. sinuosa* and *P. australis* from Warnbro and Cockburn Sounds of between 9-17 g N m^{-2} d^{-1} (Cambridge and Hocking, 1997), to yield a total seagrass nitrogen demand for Cockburn Sound of between 67-127 t N y^{-1}. Here we use an average value of 97 t N y^{-1}.

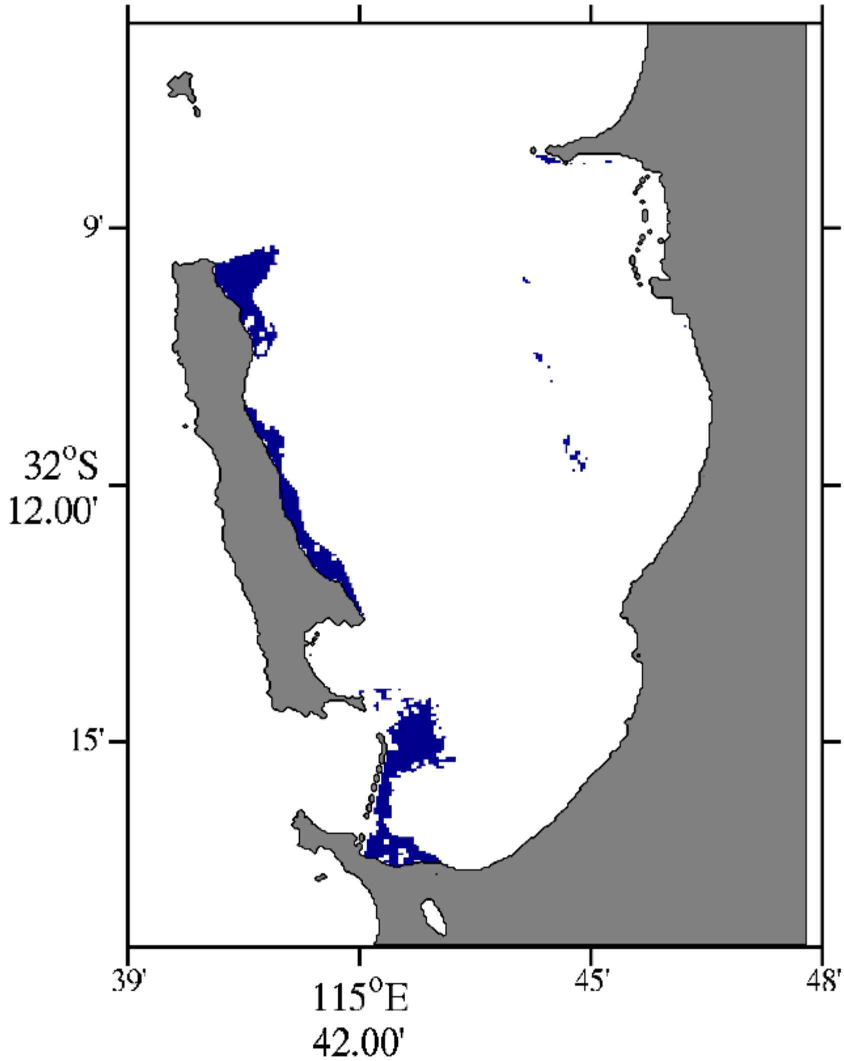

Figure 3. Seagrass coverage (blue coloration) for Cockburn Sound at 50 m resolution derived from a 2008 habitat classification. Total coverage equals 747.5 ha.

2.3.3 Epibenthic microalgae

Nitrogen demand by epibenthic microalgae (BMA) in Cockburn Sound (in mg C m^{-2} d^{-1}) is calculated based on a regional assessment reported for WA coastal waters (Keesing et al. 2011), that relates seabed light intensity with productivity (mg C m^{-2} d^{-1}) (Fig. 4). In this case, BMA productivity is further restricted to areas of soft sediment identified in a 2008 habitat data set provided by BMT Oceanica for Fremantle Ports and Cockburn Sound Management Council. This reduces the area available for BMA growth especially along the western side of the Sound where seagrass tends to dominate (Fig. 4). BMA is also somewhat reduced on the eastern shelf where small areas of rocky reef and/or periodic dredging occurs. After taking habitat considerations into account, the total annual BMA nitrogen demand was estimated to be 178 t N y^{-1}.

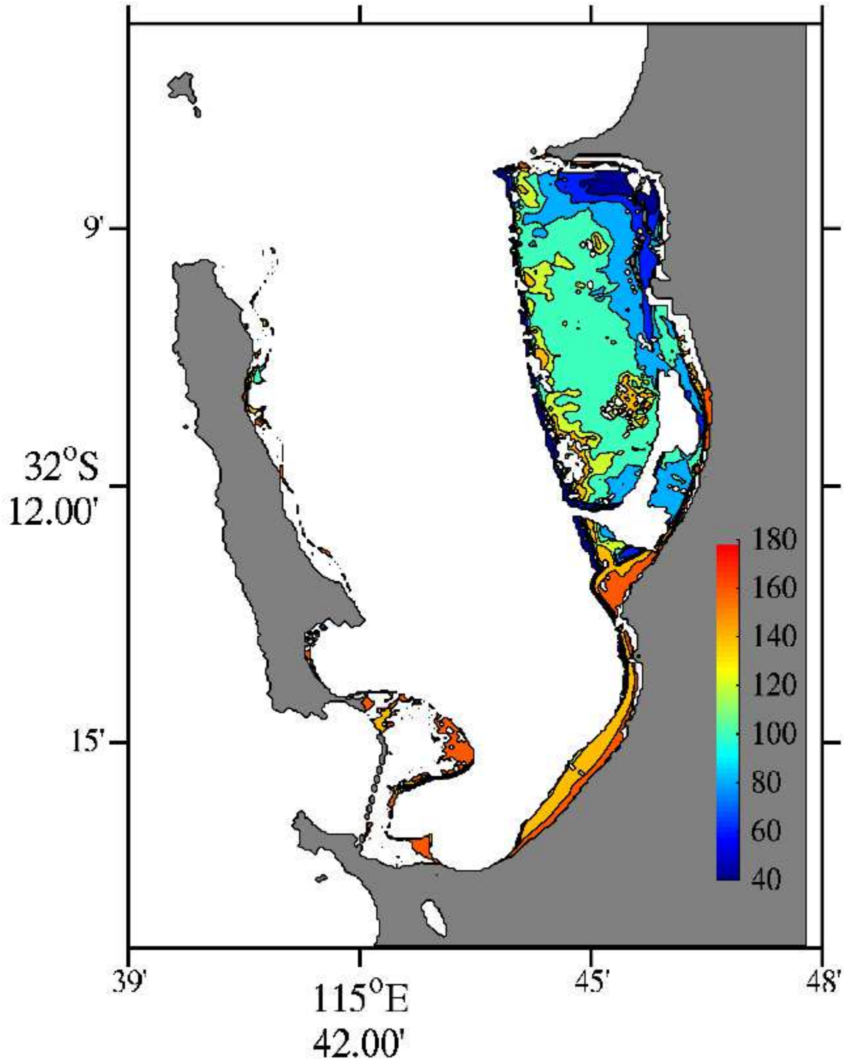

Figure 4. Estimated epibenthic microalgae (BMA) productivity in Cockburn Sound (mg C m^{-2} d^{-1}). White areas indicate where the seafloor is either dominated by seagrass (along the eastern coast of Garden Island) or the substrate is unsuitable for growth (e.g. on the eastern shelf due to rocky habitat or dredging channels), according to a 2008 habitat classification of soft sediment.

2.4 Internal recycling

It is estimated that about 84% of primary production on the WA shelf is recycled either in the water-column or at the seabed (Feng & Wild-Allen, 2010). Recycling of nitrogen is also expected to be important in Cockburn Sound. Nitrogen sediment efflux in Cockburn Sound for the year 2000 was estimated to be between 970 and 1950 t N y^{-1} accounting for between 35% and 70% of the biological demand (Fig. 1, CSMC, 2001). Elsewhere on the WA shelf, field estimates of sediment nitrogen efflux range from 0.04 – 0.10 mmol N m^{-2} h^{-1} (Rosich et al. 1994; Greenwood, 2009), and a shelf scale budget estimates it to be 0.05 mmol N m^{-2} h^{-1} (Feng & Wild-Allen, 2010). Applying these sediment efflux rates to our Cockburn Sound budget domain translates to a total nitrogen input ranging from 860-2149 t N y^{-1}, indicating a similar range to that reported earlier (Fig. 1, CSMC, 2001). Here, we

choose an average value of 1505 t N y^{-1}. The contribution of water column recycling to primary production is indicated by the so-called *f*-ratio, defined as the fraction of total biological N demand that is met by nitrate uptake as opposed to ammonium. This has not been estimated for Cockburn Sound itself, and is determined in our budget by mass balance.

3 Results and Discussion

Two separate nitrogen budgets have been prepared for Cockburn Sound, one using the lower limit of SGD nitrogen input (450 t N y^{-1}, Fig. 5), and another using the upper limit (920 t N y^{-1}, Fig. 6). The budget proposed for the lower limit (Fig. 5) is discussed first.

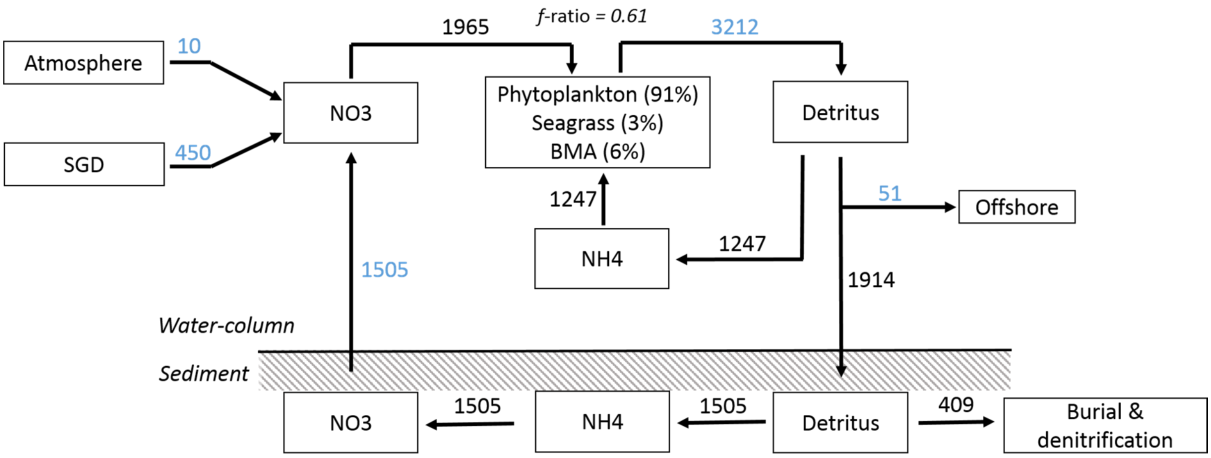

Figure 5. Nitrogen budget for Cockburn Sound (t N y^{-1}) using the lower estimated limit for SGD (450 t N y^{-1}). Fluxes in blue are calculated for this study, and those in black are derived by mass balance. NO3 and NH4 represent dissolved inorganic nitrogen in the form of nitrate and ammonium respectively, and Detritus refers to non-living organic matter that results from mortality and grazing of plants. The *f-ratio* indicates the proportion of total biological demand met by nitrate uptake.

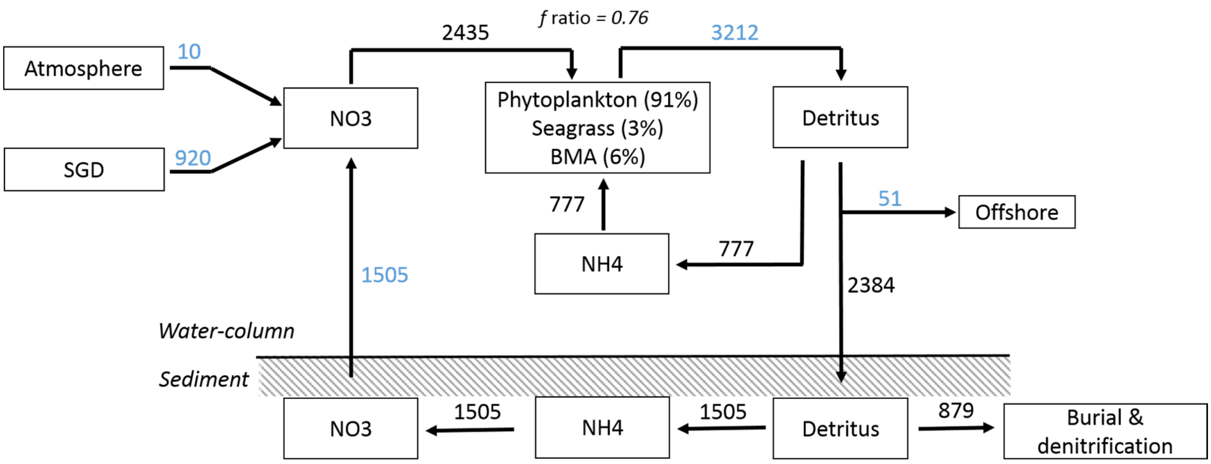

Figure 6. Alternative nitrogen budget for Cockburn Sound (t N y^{-1}) using the upper estimated limit of SGD (920 t N y^{-1}). Fluxes in blue are derived for this study, and those in black are derived by mass balance. NO3 and NH4 represent dissolved inorganic nitrogen in the form of nitrate and ammonium respectively, and Detritus refers to non-living organic matter that results from mortality and grazing of plants. The *f-ratio* indicates the proportion of total biological demand met by nitrate uptake.

The nitrogen budget that we have proposed for **the lower limit** of estimated SGD nitrogen input, is primarily constrained by accompanying estimates of sediment efflux, photosynthetic demand, and offshore export. Other fluxes (water-column recycling and sediment losses) are unknown, and are calculated as deficits to balance the budget. Importantly, the total photosynthetic nitrogen demand (phytoplankton + seagrass + BMA) exceeds the combined estimated supply from external inputs (atmosphere and SGD) and sediment efflux. We propose that the deficit is met by water-column recycling via the production of ammonium (labelled as NH4 in Fig. 5) which accounts for 39% of the total nitrogen requirement. This is not unusual in aquatic systems generally, and as noted earlier has already been established as a characteristic of biological productivity on the WA shelf. This result suggests an *f*-ratio (i.e. NO_3 uptake/NO_3+NH_4 uptake) of 0.61 compared with field estimates of 0.4-0.8 (Twomey et al. 2007), and a modelled estimate of 0.54 (Feng & Wild-Allen, 2010) for WA continental shelf waters. Nitrogen isotope-based *f*-ratios for continental shelf systems are typically a little lower ~0.4 (Chen, 2003). We assume in our budget that all the nitrogen entering the water-column from the sediment is in the oxidised form of nitrate (NO_3). However, it is not uncommon in shallow marine systems for a proportion of the sediment nitrogen flux to be in the form of ammonium (Kemp et al. 1990) which, if used utilised directly by the aquatic plants, would effectively lower the *f*-ratio.

The proportion of primary production that is recycled in the water-column has a direct bearing on the seabed deposition flux which is determined as the sum of the total photosynthetic demand (3212 t N y^{-1}) minus the rate of water-column recycling (1247 t N y^{-1}), minus export to the open sea (51 t N y^{-1}). Since this difference (1914 t N y^{-1}) is bigger than the estimated efflux of nitrate from the sediment (1505 t N y^{-1}), a proportion of it must be effectively lost in order for the budget to balance; this constituents the sediment burial/denitrification flux (409 t N y^{-1}). This flux represents 13% of primary production, compared with an estimate of 10% for the WA shelf (Feng & Wild-Allen, 2010). Again, this is not unusual. For example, denitrification in North Atlantic continental shelf sediments is estimated to be 0.69 mmol m^{-2} d^{-1} accounting for ~13% of the N incorporated into phytoplankton in shelf waters (Seitzinger & Giblin, 1996). Applying the same denitrification rate to Cockburn Sound would result in a total N loss of 370 t N y^{-1}, accounting for 90% of the sediment N loss rate required to balance our budget (Fig. 5). The only study of denitrification in Cockburn Sound reports much lower rates (~0.0024 mmol m^{-2} d^{-1}, Forehead & Thompson, 2010). However, these estimates were made using homogenised samples of the upper sediment layers (including the oxic layer) and may have underestimated denitrification in lower sediment layers. Confirmation of the magnitude of denitrification in Cockburn Sound sediments is therefore still needed.

Recent measurements of organic matter content of surface sediments in Cockburn Sound (Keesing et al., 2011) showed high levels of total nitrogen at Southern Flats and Jervoise Bay of 0.8-0.9 mg N (g dry weight)$^{-1}$ compared, for example, with a range of 0.2 – 0.4 mg N (g dry weight)$^{-1}$ measured in Marmion Lagoon. These figures suggest a legacy of relatively high levels of nitrogen deposition in Cockburn Sound consistent with our proposed budget. On average, total organic nitrogen levels in Cockburn Sound sediment (excluding the Northern Harbour) were reported to be ~0.5 mg N (g dry weight)$^{-1}$ in the top 2 cm of sediment (Keesing et al., 2011). The depth of 2 cm is significant in this case, because it corresponds with the maximum depth of dissolved oxygen penetration recorded for these sediments (Keesing et al., 2011). This exposes the top 2 cm of sediment to relatively high rates

of bacterial decay, suggesting that the organic nitrogen in this layer is making a major contribution to the sediment efflux of dissolved nitrogen. Scaling the sediment nitrogen content of the upper 2 cm for our budget domain (assuming a sediment density of 1.7 g cm^{-3}) yields a total organic nitrogen load within the top 2 cm of sediment of 1785 t N. In order to support our estimated sediment efflux of 1505 t N y^{-1}, a first order decay rate constant of 0.002 d^{-1} would be needed, which is toward the lower range of estimates for shelf seas of 0.001 – 0.01 d^{-1} (Wijsman et al., 2002; Greenwood, 2010).

In order to balance the nitrogen budget **for the upper limit** of SGD nitrogen input, a reduced reliance on water-column recycling is proposed (Fig 6). This would imply a higher *f*-ratio (0.76), heavier seabed deposition, and a larger sediment burial/denitrification rate amounting to 27% of primary production (Fig. 6). Both budgets (Figs 5 and 6) are feasible, although the *f*-ratio and sediment loss rate for the upper limit of SGD (Fig. 6) are higher than average for continental shelf waters.

According to our budget (Figs. 5 and 6), SGD inputs represent between 13% and 27% of the total nitrogen used by photosynthetic plants in Cockburn Sound (depending on whether the upper or lower limit of SGD nitrogen input is adopted), with the remainder being supported by recycled nutrients. Overall, this suggests that Cockburn Sound is primarily a recycling system, with a small relative contribution from groundwater nitrogen. Such reliance on recycled nitrogen may help to explain why chlorophyll biomass in Cockburn Sound has been slow to respond to reductions in external SGD nitrogen load, and suggests that the pelagic ecosystem will be more sensitive to changes in recycling efficiency either within the water-column or sediment, than it would to relatively small proportional changes in the external supply. For example, the possible addition of nitrogen, as a result of Managed Aquifer Recharge (MAR) estimated under a worse-case scenario to be up to a maximum of ~185 t N y^{-1} (Donn et al., 2015), would only increase the SGD contribution to ~20% for the lower limit of SGD, and 34% for the upper limit which is still a relatively minor term in the overall budget. According to the proposed budget (Figs. 5 and 6), an increase in SGD supply would either be balanced by a reduced reliance on recycled N (shift to higher *f*-ratio), or alternatively lead to enhanced plant productivity. In either case, an increase in seabed deposition would result, demanding an increase in the burial/denitrification flux in order for the N budget to stay in balance.

4 Recommendations

Further work which would help define fluxes and storages in the nitrogen budget for Cockburn Sound are listed below in priority order. These studies would also assist clarify uncertainties in the work reported by McFarlane (2015) and Keesing et al. (2016).

1. Re-sample and analyse shallow groundwater samples along the Cockburn Sound foreshore to better estimate submarine groundwater discharge of nitrogen under current conditions given that previous samples were made when nitrogen plumes were continuing to make their way towards the Sound. Specific attention needs to be given to areas around James Point and the Northern Harbour where the highest N values have been reported in the past.
2. Measure phytoplankton productivity in Cockburn Sound including spatial and seasonal variability. According to our preliminary budget calculations 90% of the biological nitrogen demand in Cockburn Sound is attributed to phytoplankton. Our estimate is based on modelled phytoplankton productivity because no field measurements have been made to date. New field measurements of phytoplankton productivity are needed to better estimate the biological demand, and constrain the water-column recycling and seabed deposition flux.

3. Re-measure sediment denitrification rates in Cockburn Sound including spatial and seasonal variability to better estimate the sediment nitrogen loss term. Our calculations suggest that this flux needs to be much larger than previous estimates have suggested in order for the nitrogen budget to balance. Verification of this is needed to assess how the sediments will respond to any additional nitrogen loading.
4. Make new measurements of sub-surface sediment chemistry using micro-electrodes to provide validation data for numerical modelling of sediment diagenesis. This is needed to better estimate burial and nitrogen efflux from the sediment. It will also provide an independent estimate of sediment denitrification.

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