Environmental Research in Macquarie Harbour

Interim Synopsis of Benthic and Water Column Conditions

Jeff Ross & Catriona MacLeod

January 2017

Prepared for the EPA and DPIPWE

Institute for Marine and Antarctic Studies, University of Tasmania, Private Bag 49, Hobart TAS 7001

Enquires should be directed to:
Dr Jeff Ross
Institute for Marine and Antarctic Studies
University of Tasmania
Private Bag 49, Hobart, Tasmania 7001, Australia
Jeff.Ross@utas.edu.au
Ph. (03) 6226 8281
Fax (03) 6226 8035

The authors do not warrant that the information in this document is free from errors or omissions. The authors do not accept any form of liability, be it contractual, tortious, or otherwise, for the contents of this document or for any consequences arising from its use or any reliance placed upon it. The information, opinions and advice contained in this document may not relate, or be relevant, to a reader's particular circumstance. Opinions expressed by the authors are the individual opinions expressed by those persons and are not necessarily those of the Institute for Marine and Antarctic Studies (IMAS) or the University of Tasmania (UTas).

© The Institute for Marine and Antarctic Studies, University of Tasmania 2017.

Copyright protects this publication. Except for purposes permitted by the Copyright Act, reproduction by whatever means is prohibited without the prior written permission of the Institute for Marine and Antarctic Studies.

BACKGROUND

The Macquarie Harbour water column is highly stratified due to the significant freshwater inputs from the Gordon and King Rivers, deep central basin (maximum depth ~ 50m) and shallow sill at its mouth (<5 m) that restricts exchanges with the ocean. This isolation of deep waters in the Harbour has resulted in a naturally low dissolved oxygen (DO) environment (Creswell et al., 1989; Koehnken 1996). The dark tannin rich freshwater layer limits light penetration and as a consequence productivity is low; the sediments are naturally depauperate of fauna (O'Connor et al. 1996; Talman et al. 1996; Edgar et al. 1999)

Since the late 1980's the Harbour has been a site for caged finfish (salmon and trout) aquaculture. Production has steadily increased over the years reaching 9,000 tonnes in 2011. In 2012 an expansion lease area was approved and subsequent stocking from 2013 has seen a further increase in production, with production approaching 16,000 tonnes in 2015. In March 2016, the allowable cap for production was 21, 500 tonnes, to be reviewed in early 2017.

In late 2013 a decline in DO levels in the bottom waters of the Harbour was confirmed. To investigate this issue the Tasmanian Salmonid Growers Association (TSGA) established the Macquarie Harbour Dissolved Oxygen Working Group (MHDOWG). Since then studies have investigated Harbour oxygen dynamics, with an emphasis of identifying the drivers of oxygen resupply and consumption to help determine attribution for the observed decline (MHDOWG 2014, Revill et al. 2015, Ross et al. 2016; Maxey et al. 2016). In mid-2014 there was a significant recharge of bottom waters, but oxygen levels have since declined back to very low levels.

Since mid-2013 changes in benthic condition have presented in the Harbour, with routine benthic monitoring showing an increase in the abundance and distribution of opportunistic polychaetes on the sediment surface in and around marine farming leases (Macquarie Harbour Status Report February 2015). Investigating these observed changes was the subject of a tactical Fisheries Research and Development Corporation (FRDC) research project (2014/038) in early 2015 (Ross et al., 2015) and is the focus of ongoing research in FRDC Project 2015/024. Results from the most recent benthic survey in October 2016 have shown a significant decline in both macrofaunal abundance and the number of species recorded across all study leases and at a number of the external sites. Spring 2016 remotely operated vehicle (ROV) compliance monitoring conducted just prior to the FRDC October survey highlighted a major increase in the presence of the *Beggiatoa* matts on the sediment surface in and around a number of the marine farming leases.

In light of the recent benthic observations and return to very low DO levels in bottom waters, the Environment Protection Authority (EPA) and Department of Primary Industries, Parks, Water and Environment (DPIPWE) have requested IMAS provide an interim synopsis of the science and current status of the benthic and water column environments.

In the first part of the synopsis we provide a brief summary of the key research projects and their findings with a focus on the ecology and condition of the Harbour benthic and water column environments. This provides important context for the subsequent presentation and discussion of the latest observations[1] and current status

[1] This report is written in the context of environmental data available up until the end of October 2016

of the Macquarie Harbour environment. We finish with a discussion of suggested research priorities aimed at improving our understanding of the current situation that will assist management in the short to long term.

It is important to acknowledge that this is an 'interim' synopsis of what we, the authors, believe are the key research findings in the context of the current observations of the Harbour environment. It is not an exhaustive and detailed presentation of all available science. Further detail can be found in the respective reports.

BENTHIC CONDITION AND ECOLOGY

Historically, much of the research on ecosystem health in the Harbour has focused on the effects of heavy metal contamination on benthic conditions from past deposition of mining tailings and acid drainage from upstream mining activities in the King River catchment (Koehnken 1996). Benthic invertebrate communities were chosen as a biomonitor of ecosystem health in Macquarie Harbour as part of the Mount Lyell Remediation and Research and Demonstration Program (1996). The results of the benthic invertebrate survey in 1995 highlighted the low invertebrate diversity and abundance when compared to other coastal embayments elsewhere in south-eastern Australia, with copper contamination and the availability of organic matter considered the main determinants of benthic invertebrate abundances, diversity and community structure (Talman et al. 1996). A subsequent statewide assessment of the ecological attributes (benthic invertebrates, fish and plants) of Tasmanian estuaries by Edgar et al. (1999) also described extremely low species richness, invertebrate biomass and secondary productivity in Macquarie Harbour, but noted that this was also a general pattern observed in west coast estuaries. Notwithstanding the likely effects of heavy metal contamination, Edgar et al. (1999) concluded that the low abundance and production of fauna in western and southern Tasmanian estuaries probably results from very low primary productivity and a paucity of available food; the low productivity and concomitant limited availability of food largely due to low light penetration from the high levels of tannin rich freshwater sources and limited inputs of nutrients in the surrounding catchments.

In considering the planning application by the salmonid industry to expand farming in the Harbour, the Marine Farming Planning Review Panel (MFPRP) identified that research was required to understand the role that benthic sediments play in the cycling of organic matter and nutrients in the Harbour. Similarly, the MFPRP identified that research was required to more fully understand the potential impacts of the proposed farming operations on the ecology of the Maugean Skate – a species listed as endangered under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) and the *Threatened Species Protection Act 1995*. Both of these knowledge gaps were addressed by IMAS in FRDC projects 2012/047 and 2013/005; the key findings of relevance to the current environmental conditions in the Harbour are briefly summarised below. Similarly, a summary of the findings of FRDC 2014/038, investigating the increase in the abundance and distribution of opportunistic polychaetes on the sediment surface in and around marine farming lease areas is also provided given the relevance to recent benthic observations in the Harbour.

FRDC Project Number: 2012/047 Characterising benthic pelagic interactions in Macquarie Harbour - organic matter processing in sediments and the importance for nutrient dynamics (Ross et al. 2015)

A key knowledge gap in Macquarie Harbour was a lack of ecological data on the capacity of sediments to process organic matter and nutrients, particularly given the expectation of increased localised organic loads associated with expanded farming (see Figure 1). Sediment - water column nutrient fluxes were measured at sites on and off-farm within the Harbour (Figure 2). This was achieved by collecting sediment cores and measuring changes in nutrient concentrations over a fixed incubation period. As expected, based on the relative levels of organic matter input, rates of organic matter mineralisation were significantly lower at Harbour and farm control sites compared to cage sites. Comparing the ratio of oxygen consumed with dissolved inorganic carbon produced during respiration highlighted the increasing role of anaerobic respiration at sites enriched by farm inputs (Figure 3). Patterns of ammonium production largely reflected the patterns of respiration with higher rates at farmed sites compared with Harbour and farm control sites (Figure 4). Nitrate fluxes were predominantly directed into the sediments at all sites, which is consistent with conditions in low oxygen environments where nitrification (the process by which ammonia is converted to nitrate in oxic conditions) is limited and denitrification (the process by which nitrate is converted to nitrogen gas in anoxic conditions) must rely on sourcing nitrate from the water column rather than from nitrate produced in the sediments via nitrification. Rates of denitrification (the process that permanently removes nitrogen from the system) also reflected patterns of organic enrichment with higher rates at farmed sites compared with Harbour and farm control sites. However, in the context of the total nitrogen budget, although denitrification rates are higher at farm sites, the percentage of nitrogen removed via denitrification is in fact lower in sediments at farm sites compared to the broader Harbour or farm control sites. This is due to the very high efflux of ammonium back into the water column at the farm sites.

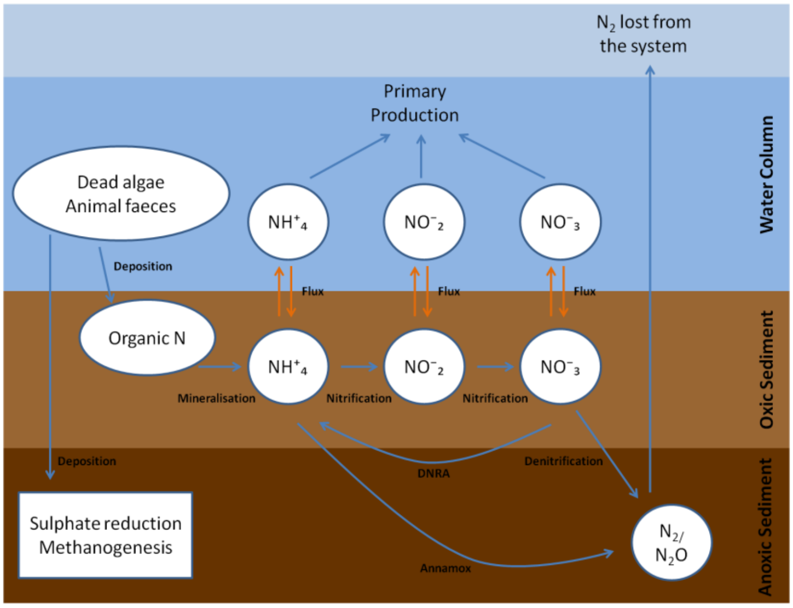


Figure 1 Simplified schematic and description of organic matter and nitrogen cycling in coastal sediments In sediments, most processes start when organic matter (OM) is mineralised. The mineralisation process of OM occurs through bacterial respiration and this process consumes oxygen (O2) and produces carbon dioxide (CO2). In anaerobic sediments, mineralisation may also take place through the processes of sulphate reduction and methanogenesis due to the lack of oxygen, which produce hydrogen sulphide and methane gases respectively. Initially ammonia is also produced, some of which is released back into the water column and this can fuel more phytoplankton growth. Where surface sediments are oxygenated (oxic) the ammonia is also converted to nitrate via the process of nitrification. The nitrate can then also be released back into the water column to fuel more phytoplankton growth, or under more anoxic conditions, it can be converted to nitrogen gas via the process of denitrification. Nitrogen gas is then lost from the system, unavailable to fuel algal growth.

It is clear that the Macquarie Harbour ecosystem and the associated biogeochemical processes are different from that previously described for other systems in Tasmania. The study highlighted the importance of anaerobic processes and the production of reduced compounds in benthic biogeochemistry of the Harbour. If these reduced compounds are reoxidised in bottom waters the concomitant oxygen demand is not likely to be fully accounted for in benthic core incubations. The very low bottom water oxygen conditions in the final two surveys highlight the importance of understanding the major drivers of oxygen dynamics in bottom waters; the potential role of reduced compounds warrants investigation.

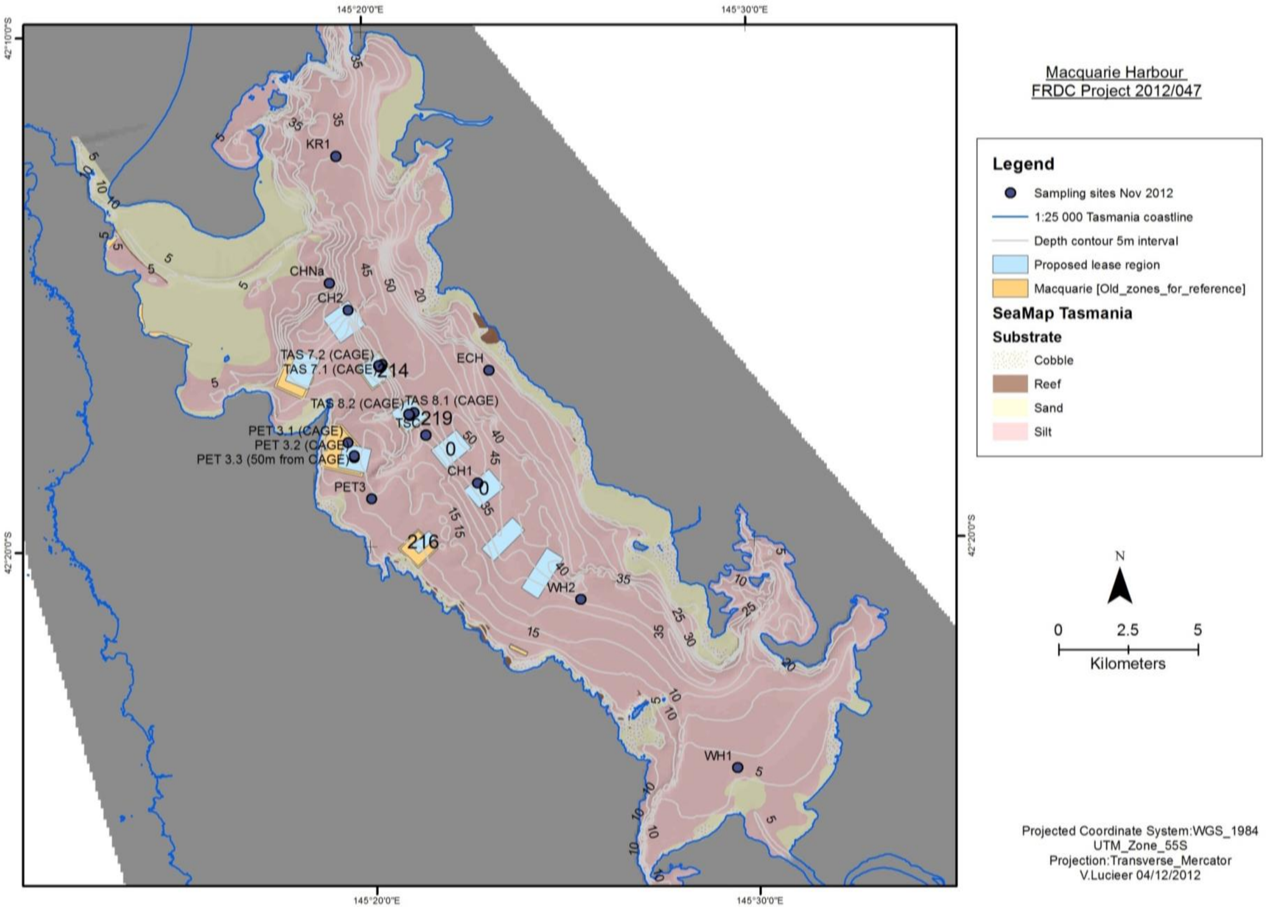


Figure 2 Map of Macquarie Harbour showing survey sites. Note the labelling at farm sites refers to the zone number (e.g. TAS 7, TAS 8 and PET 3), cage number (e.g., TAS 8.1,8.2; TAS 7.1,7.1; PET 3.1,3.2 refer to cages 1 and 2 at each farm) and 50m from cage site (e.g. TAS 8.3, TAS 7.3 and PET 3.3).

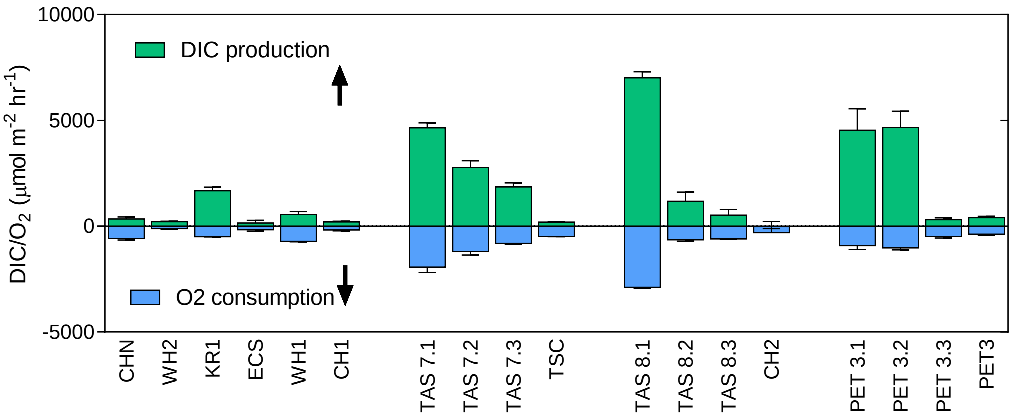


Figure 3 Sediment respiration: comparison of O2 and DIC fluxes (µmol m-2 h-1) (± standard error (SE)) in November 2012. Note, sites 8.2 and 3.2 were fallowed at the time of sampling.

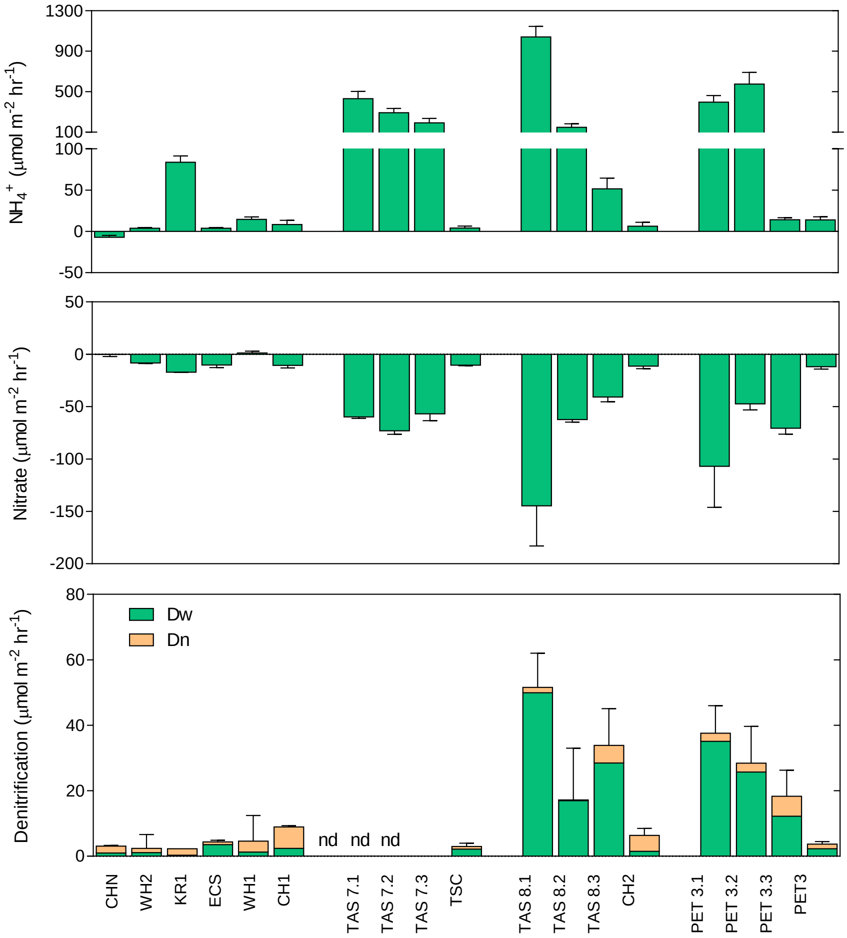


Figure 4 Sediment-water nitrogen fluxes from November 2012. Ammonium (NH4), nitrate (NO3), and denitrification (N2) (µmol m-2 h-1) (± SE). For denitrification subscript w represents water-column-driven nitrate reduction and subscript n nitrate sourced from sediment nitrification. nd represents no data. Note, sites 8.2 and 3.2 were fallowed at the time of sampling.

FRDC Project Number: 2013/008 Movement, habitat utilisation and population status of the endangered Maugean skate and implications for fishing and aquaculture operations in Macquarie Harbour (Bell et al. 2016)

To determine the distribution, habitat utilisation and movement of the Maugean Skate in Macquarie Harbour, an extensive array of acoustic receivers was placed throughout Macquarie Harbour (Figure 5). This array comprised several curtains to assess Harbour wide movements, along with a high density of receivers amongst the marine farms and in areas where Maugean Skate are abundant and recreational gillnetting is common. A total of 58 Maugean Skate were acoustically tagged at multiple locations in the Harbour. To determine the key biological characteristics of the skate, including population size, reproductive dynamics and feeding habits, seasonal biological sampling was conducted over a period of 15 months. Reproductive status was assessed using non-destructive techniques (endocrinology and ultrasonography) and stomach lavage was used to investigate diet. A preliminary assessment of metabolic response to varying levels of DO was also undertaken experimentally. All skate were Passive Integrated Transponder (PIT) tagged prior to release and population size estimated using tag recapture rates throughout the study period.

Maugean Skate generally displayed a high degree of site fidelity, with 50% and 95% utilisation distributions generally <3 and <10 km^2 respectively (Figure 5). Based on the number of detections, Maugean Skate spent 85% of their time at 6–12 m depth, although they were detected from 0.6 m to >55 m, albeit rarely, indicating they are not restricted to their preferred depth range (Figure 6).

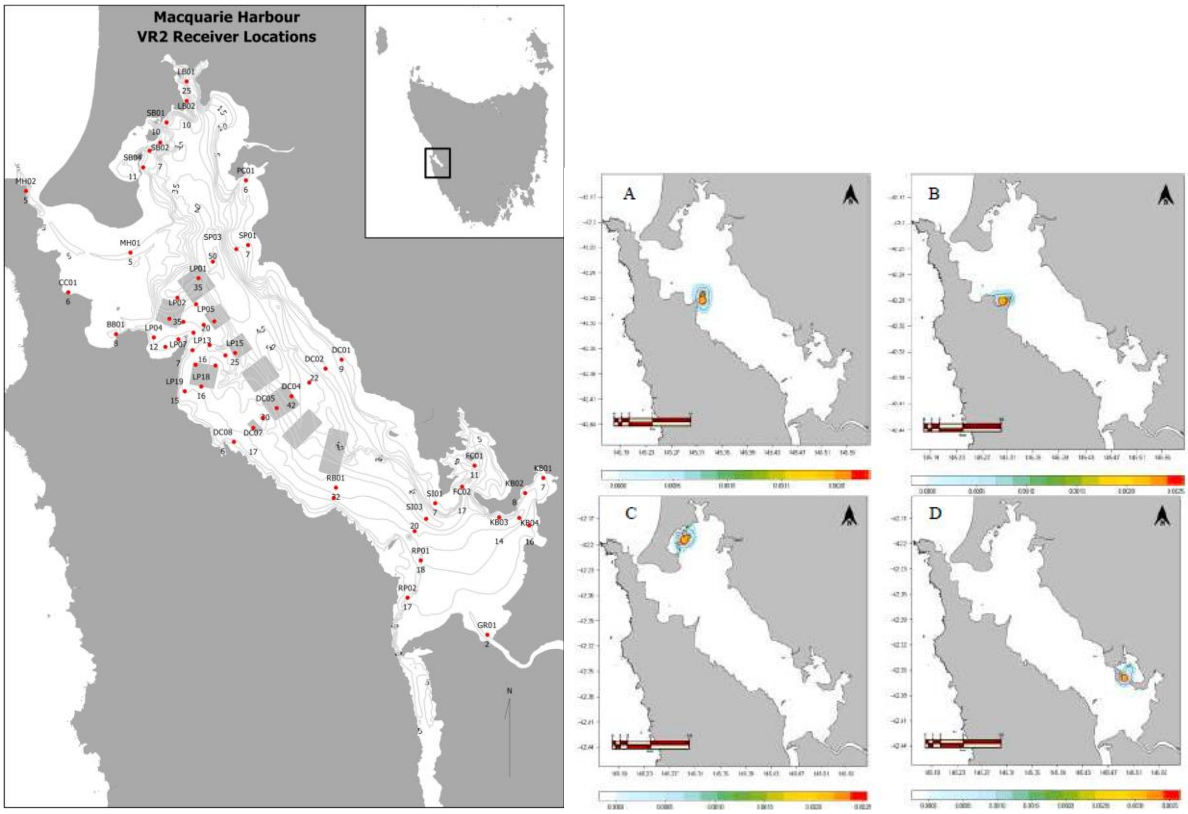


Figure 5 Map showing VR2 (red circle) names and locations (left panel) and utilisation distributions of selected Maugean Skate displaying differing home ranges (right panel).

Skate depth utilisation appears to be dictated by water chemistry with shallow waters having low salinity and high temperature variability, whereas deeper waters are stable in terms of temperature and salinity but have low concentrations of DO (<20%). Low DO concentrations appear limiting for the skate and presumably their prey. Waters in their preferred depth range tend to have relatively stable temperature (12–15 °C), salinity (18–27 ppt) and generally retained moderate DO concentrations (>30%). The importance of water chemistry was illustrated in their response following the oxygen recharge event in late July 2014 (Figure 7), with increased depths utilised following the recharge.

Skate were more active during the night and moved into shallower water, which possibly represents nocturnal foraging behaviour. Maugean Skate have a restricted diet dominated by three groups of epibenthic crustaceans, namely crabs, carid shrimp and mysids.

Males and females matured at significantly different sizes; 50% maturity was attained at 632 mm total length (TL) in males (based on clasper size and condition) and 662 mm TL in females (based on maximum follicle diameter). Preliminary estimates of age from sectioned vertebrae for thirteen Maugean Skate suggest that the species is likely to be relatively short lived (maximum age observed of 11 years) but may live to about 15+ years. Maximum age (and size) is a useful proxy for productivity in skates and these results suggest that Maugean Skate are probably relatively productive.

The species is only known from two Tasmanian estuaries and when considered in the context of their preferred habitat (predominantly 6–12 m) means they probably also have one of the smallest distributions of any chondrichthyan. The best estimate of the population size in Macquarie Harbour was in the order of 3200 individuals, likely the smallest of any chondrichthyan species. There are, however, potential biases in this assessment that suggest it may be an underestimate and thus a feasible minimum possible population size.

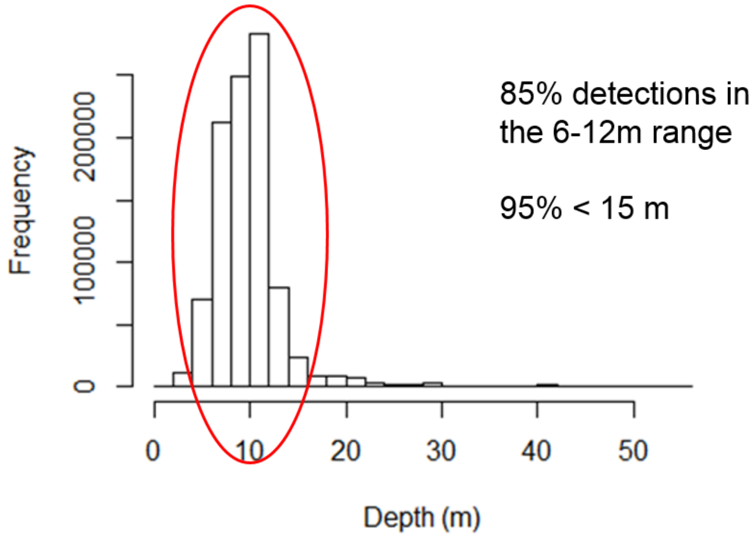


Figure 6 Frequency of detections by depth for all tagged Maugean Skate combined.

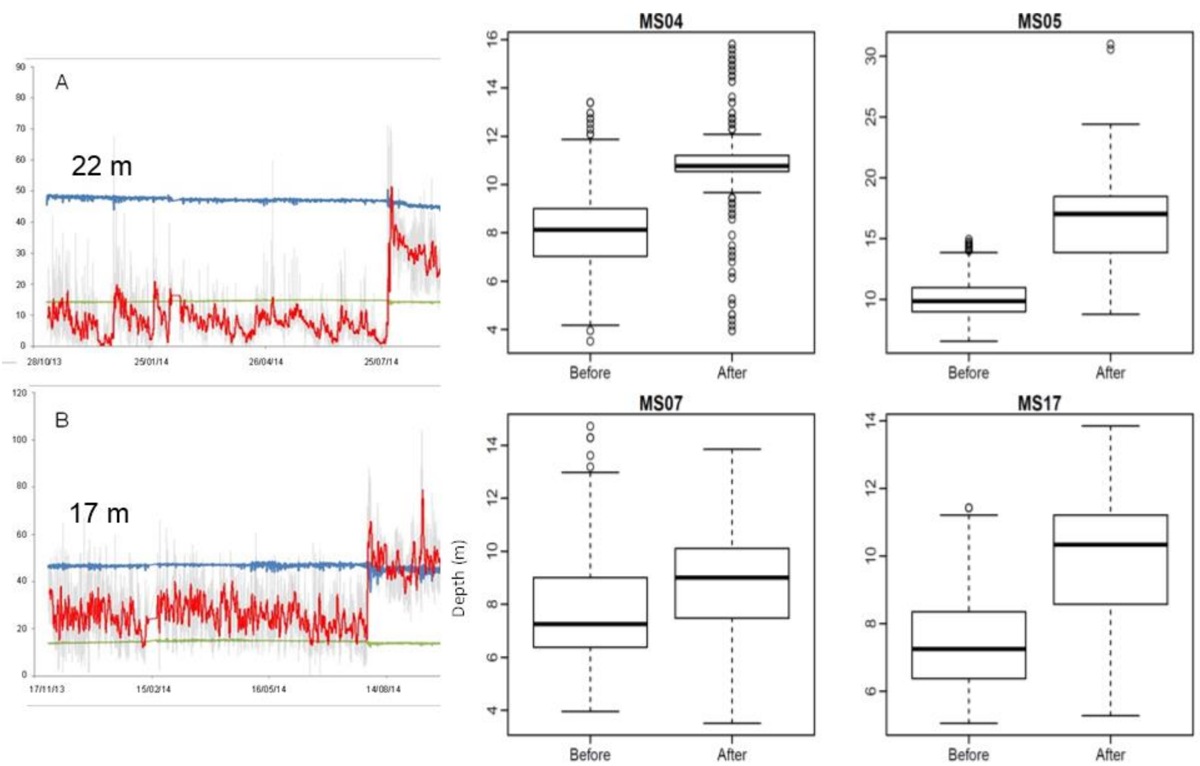


Figure 7 Variation in temperature and DO throughout the study period at a site at (A) 22 m depth and (B) 17 m depth off Liberty Point during the study period showing the oxygen recharge in late July. Depth utilisation (detections) of Maugean Skate with >500 detections in the week before and after the recharge event.

Direct interactions between Maugean Skate and aquaculture operations appear to be limited. The aquaculture industry expansion strategy in Macquarie Harbour involves the location of new lease sites into the deeper regions which, given the Maugean Skate's preference for shallower depths, means that there is minimal overlap between core skate habitat and the marine farm lease sites. There may, however, be indirect interactions, for instance the production of organic wastes associated with marine farming operations increases biological oxygen demand and acts to reduce DO as well as enriching of the pelagic environment through the excretion of dissolved nutrients (*e.g.* ammonium and nitrate). The recent downward trend in DO levels of the deep-waters (>15m) of Macquarie Harbour corresponded with the timing of this study and it is likely that reduction in bottom DO will have negatively influenced the area of core habitat (preferred depths). Furthermore, while the depths at which Maugean Skate deposit eggs is uncertain at least some eggs are deposited in depths greater than about 20 m suggesting they could now be exposed to low DO concentrations. Developing embryos are unable to move away from unfavourable conditions and are therefore forced to rely on coping mechanisms rather than avoidance.

FRDC 2014-038: Understanding Dorvilleid ecology in Macquarie Harbour (Ross et al. 2016)

Previous research has shown a clear impact gradient associated with cage salmon farming operations, and that presence of bacterial mats (*Beggiatoa spp.*) and proliferation of opportunistic species are features commonly associated with high levels of organic enrichment. The presence and abundance of these species can be used as an indication of deteriorating environmental conditions. For example, the presence of numerous annelid opportunists, such as Capitellid worms, 35m outside the boundary of the lease area, may be interpreted as representative of "unacceptable impact". In southern Tasmania, Capitellid worms are the key opportunists associated with high levels of organic enrichment (Macleod and Forbes 2004). The understanding that proliferating opportunists represents deteriorating conditions was translated to monitoring protocols in Macquarie Harbour. Although the relationship between opportunists and the level of enrichment was not explicitly tested in this region, video surveys in Macquarie Harbour suggested that in this region Dorvilleid worms rather than Capitellids were the species most indicative of organic enrichment effects. However, recent responses of the benthos in Macquarie Harbour to enrichment from salmonid aquaculture have appeared to be somewhat inconsistent with expectations developed from southern Tasmanian regions. This project was designed to enhance understanding of the ecology of Dorvilleid polychaetes in Macquarie Harbour and their response to organic enrichment from fish farming.

Benthic grabs and sediment cores were collected to assess the relationship between benthic communities and organic enrichment. Estimates of Dorvilleid abundance from benthic grabs and ROV footage were also compared. The sites were positioned along the enrichment gradient of each of the four leases sampled using a cross hair design, i.e. 4 transects radiating out from the lease at approximately 90 degrees to each other, with samples collected at 5 positions on each transect (0m, 50m, 100m, 250m and 500m from cages). In addition, 18 external sites were sampled that were at least 1km, but up to 10km, from the leases (Figure 8).

Both species of Dorvilleids, *Ophryotrocha shieldsi* and *Schistomeringos loveni,* appear to be good indicators of organic enrichment from salmon farming in

Macquarie Harbour (Figure 9). However, their presence reflects different levels of enrichment; *O. shieldsi* occurred predominately as colonies directly under stocked cages and was only occasionally observed out to 50m whereas the peak abundance of *S. loveni* was further away from the stocked cages at 50-100m. These results suggest that *S. loveni* is less tolerant of the conditions associated with highly enriched sediments (i.e. as would be found directly adjacent to stocked cages).

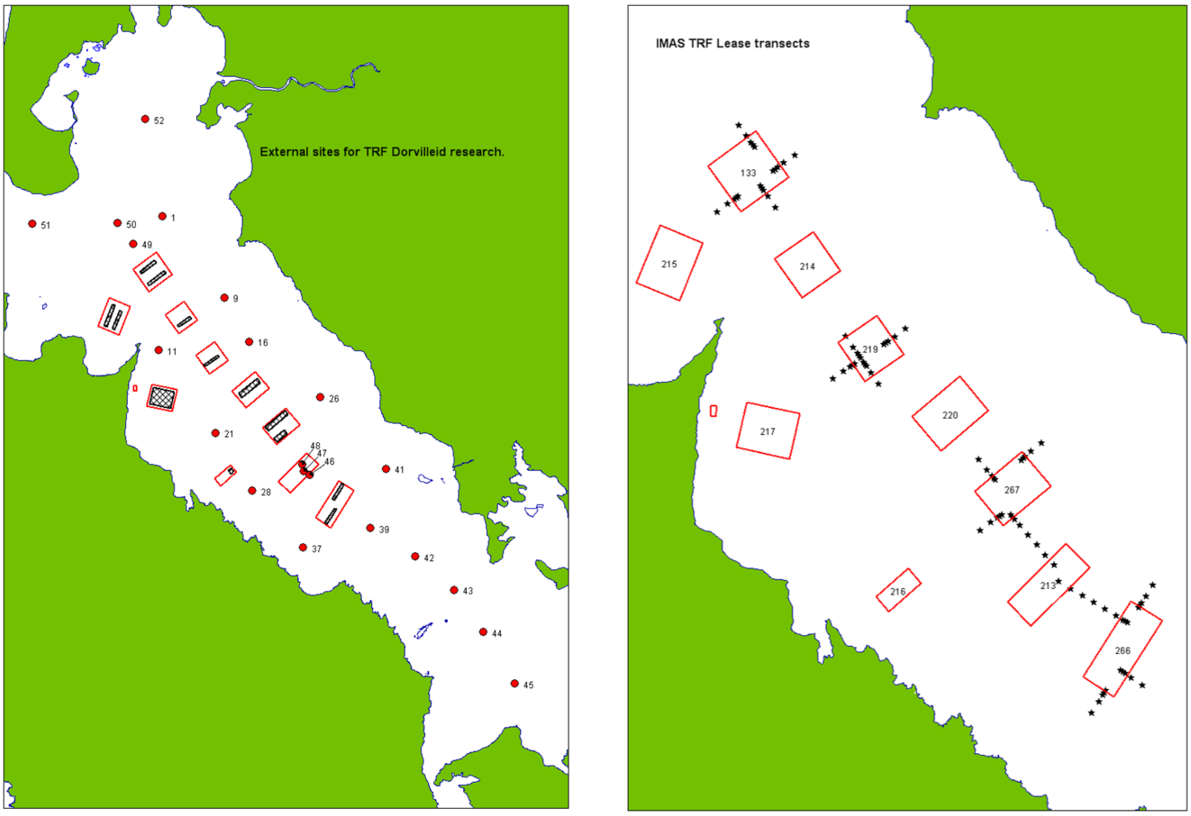


Figure 8 Maps showing external (left) and lease (right) sites.

Although the distribution of each of the Dorvilleid species was patchy, both within and between leases, there were some broad patterns in their distribution which could be related to feed inputs and farm history. When feed inputs were low, the peak abundance of *S. loveni* was observed to be closer to the cage and where feed input was high, peak abundance of *S. loveni* was at a noticeably greater distance and in this instance both *O. shieldsi* and *Beggiatoa* were more common. These effects appeared to be exacerbated at leases which had been operational for a long time, with *O. shieldsi* and *Beggiatoa* persisting for longer and *S. loveni* reaching higher abundances in these situations.

Changes in the composition of benthic communities were broadly consistent with that expected in response to organic enrichment but appear to be occurring at an increased spatial scale in Macquarie Harbour (i.e. at greater distances from the source (cages) than observed in the southern regions). Peak faunal abundance and species richness occurred at 50m and 100m, respectively, while species diversity increased from approximately 100m. At a functional group level burrowing/epibenthic fauna (mostly *S. loveni* and *Nebalia sp.*), were found to dominate out to 100m, but beyond this point tube building species (mostly Sabellid fan worms) dominated.

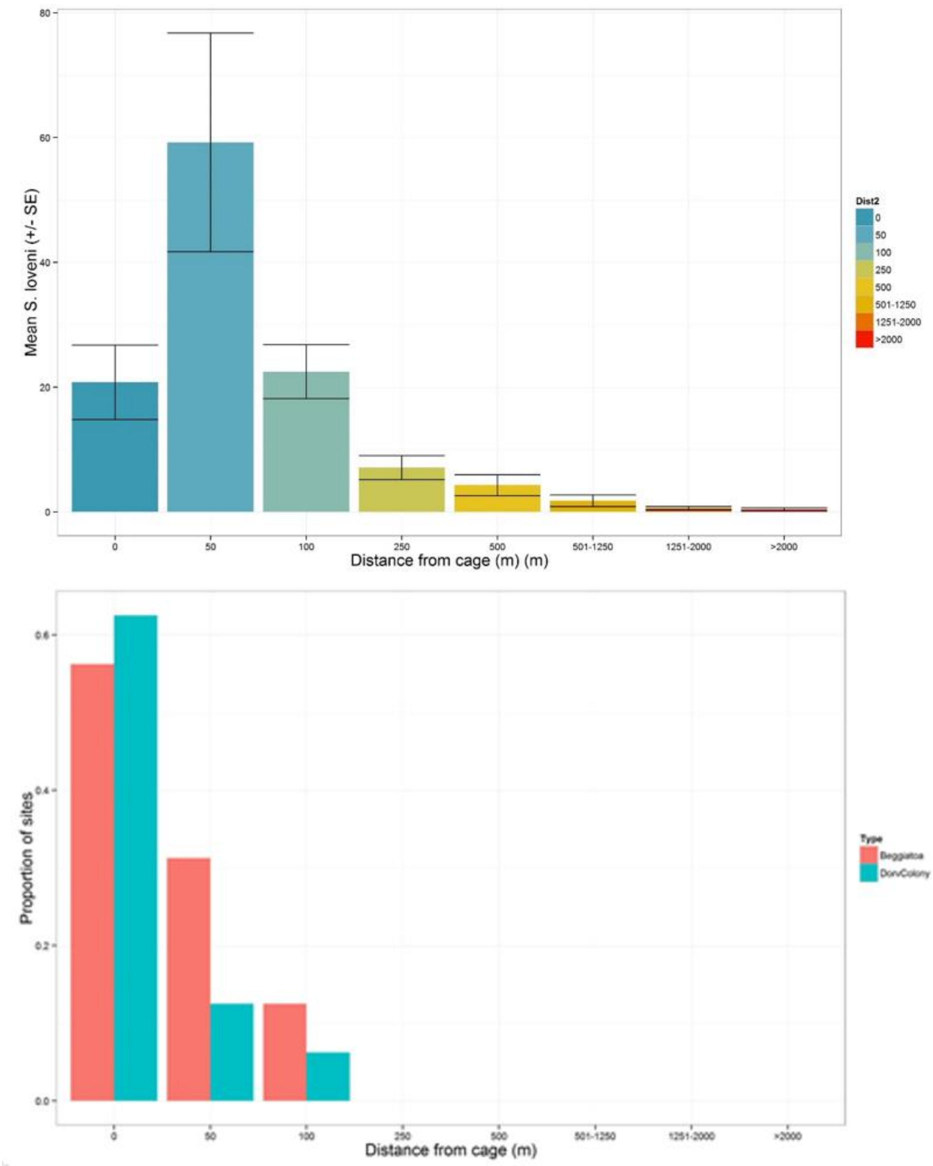


Figure 9 Mean abundance of *Schistomeringos loveni* at sites with increasing distance from salmon cages (top panel) and proportion of sites with colonies of *Ophryotrocha shieldsi* and *Beggiatoa* per lease (bottom panel).

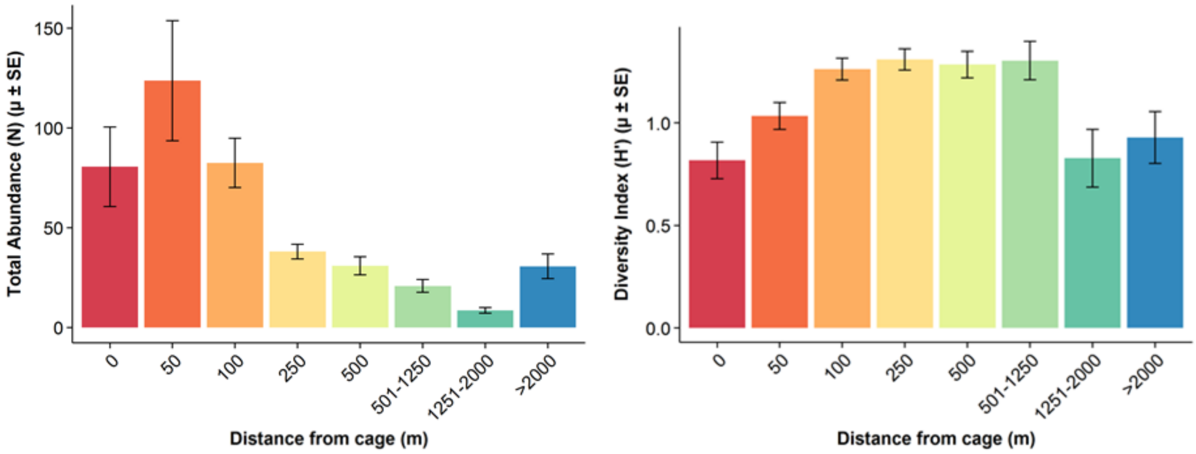


Figure 10 Mean total abundance of all taxa, and Shannon-Weaver diversity index per 1mm grab sample with increasing distances from cages, including external sites. Values are means, error bars indicate standard error. *Figure reproduced from Ross et al. 2015.*

The comparison with baseline surveys highlighted a change in the broader benthic ecology over the past 15 years, and arguably mostly in the last 2 years, with a measurable increase in total abundance, species richness and species diversity. These observed changes have also had an influence at a functional level, with a decrease in burrowing taxa and an increase in tube builders (both suspension and deposit feeding). Whilst there could be a range of explanations for this change, such as a recovery from the effects of mining or influx of organic matter associated with changes in the regulation of catchment inflows, it is highly likely that the addition of nutrients and organic matter from fish farming has played some role in stimulating benthic productivity.

Estimates of Dorvilleid abundance from the ROV footage were compared with actual measures of abundance from Van-veen grabs and the results proved to be very enlightening. Interestingly the ROV was the most reliable approach for detection of colonies of *O. shieldsi*. This observation is particularly important given *O. shieldsi* appears to be the species most associated with *Beggiatoa* and an indicator of particularly high levels of enrichment. In contrast the ROV was not as reliable for the determination of the abundance of *S. loveni,* as this species would appear to reside both on the sediment surface and deeper in the sediments. It may be that the presence (or absence) of this species on the sediment surface, and as a result in the ROV footage, is a function of sediment and bottom water conditions and that *S. loveni* may come to the surface when sediment oxygen levels decline. If this is the case and the relationship can be established, then the ROV footage could be standardised accordingly. However, the behavioural ecology of *S. loveni* demonstrated that the ROV at present cannot provide a reliable indicator of this species' presence or relative abundance.

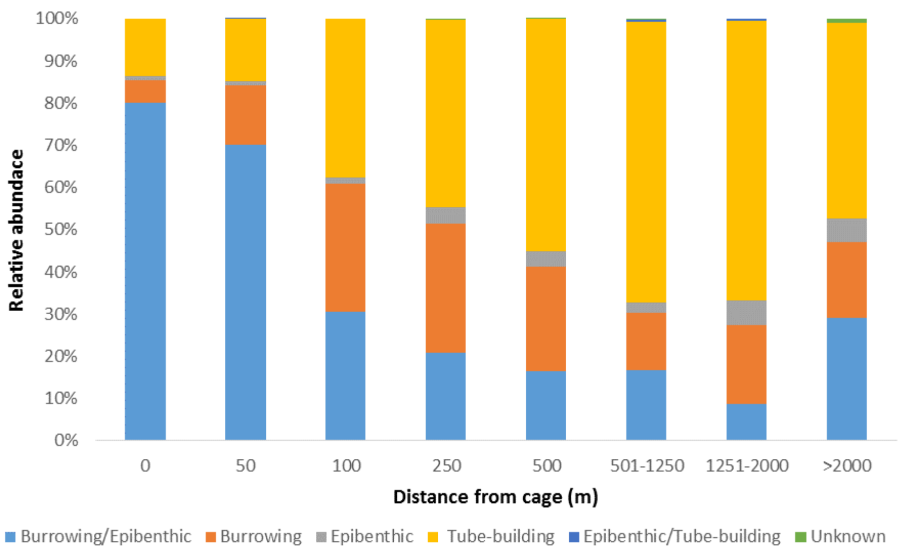


Figure 11 Relative abundance of benthic functional groups with distance from cage. *Figure reproduced from Ross et al. 2015.*

The findings of the current study would suggest that *O. shieldsi* is perhaps the species that would be most useful as an indicator of "unacceptable impact". This colony forming species was regularly observed in close association with stocked cages and in the presence of the anoxic/ hypoxic bacterial species *Beggiatoa*. This association would suggest that the presence *O. shieldsi* at compliance monitoring sites could be considered as representative of "unacceptable impact". On the other hand, *S. loveni* was found to be less tolerant of highly enriched sediments and interpretation of the presence of this species is more ambiguous. For example, *S. loveni* can occur at similar densities that are likely to reflect different levels of impact. They can be present closer to cages where conditions are deteriorating and relatively poor, and the benthic community might otherwise be considered to be highly disturbed (i.e. where there are few species and these tend to be dominated by burrowing and epibenthic taxa). However, a similar number of *S. loveni* may also be present further from the cages and associated with more moderate levels of enrichment and a more diverse community indicative of improving conditions. As a result, it is suggested that more context would be required when seeking to interpret the presence of *S. loveni* and the level of impact. It is hoped that repeat surveys, currently underway through FRDC project 2015-024, will provide greater insight into the processes underpinning the variability and potential usefulness of *S. loveni* as an indicator species.

WATER COLUMN CONDITION

Low DO concentrations are a common feature in fjord-like systems with deep central basins, a shallow sill that limits coastal exchange (Figure 12) and a stratified water column due to significant large freshwater inflows. In Macquarie Harbour DO levels in middle bottom waters (>15m) have typically ranged between 40 and 70% saturation based on long term EPA records. These relatively stable levels of DO in the Harbour from 1993-2009 suggest tight coupling between consumption (i.e. demand) and renewal (i.e. supply) of DO (MHDOWG 2014). In late 2013 a trend of declining DO levels in the middle and bottom waters was highlighted by the EPA (Figure 13). As a result, industry

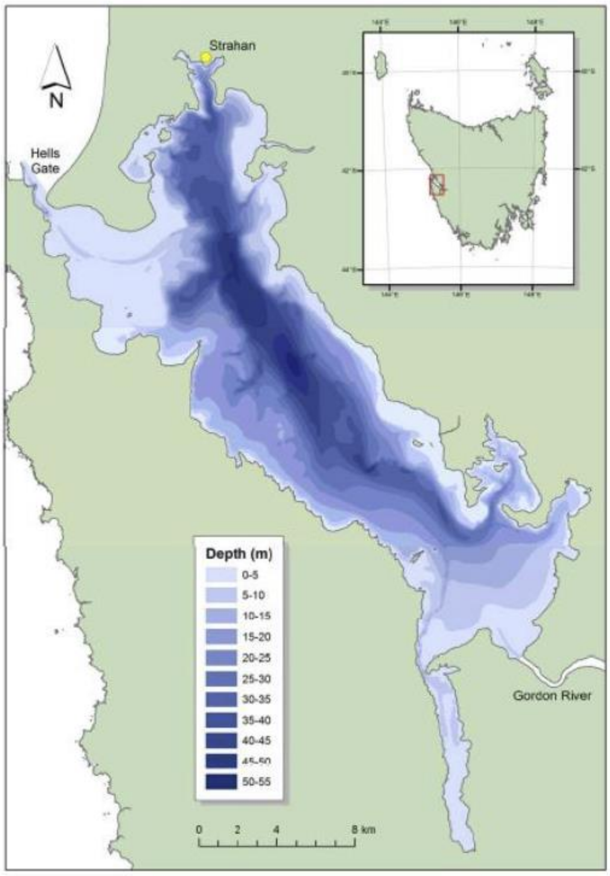


Figure 12 Bathymetry in Macquarie Harbour (from Lucieer et al 2009).

established a Macquarie Harbour Dissolved Oxygen Working Group (MHDOWG) to verify the observed DO trend, and investigate possible causes, which broadly fall into two categories: processes associated with DO consumption; and processes associated with DO renewal. The key findings of the final report, update reports and associated studies are discussed below.

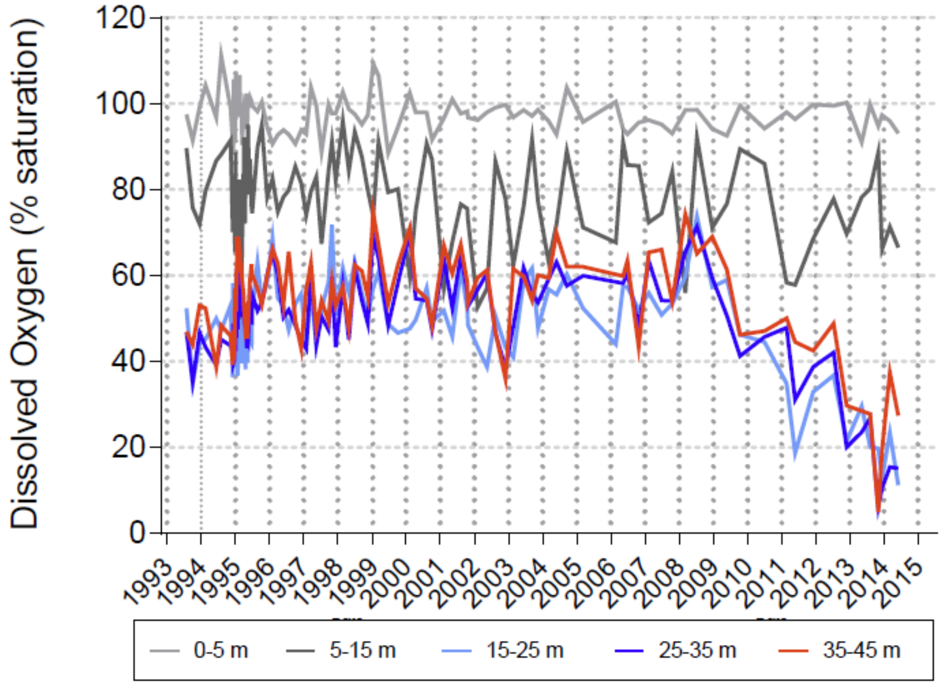


Figure 13 Long term trend in DO within a number of depth ranges at EPA site 12 (from MHDOWG 2014).

Oxygen Consumption

The rates of sediment oxygen consumption and carbon dioxide production measured as part of FRDC 2012/047 were used to calculate the contribution of farming to the benthic biological oxygen demand (BOD), and aquaculture was estimated to be responsible for between 3 and 12% of the benthic BOD in Macquarie Harbour (for sediments deeper than 15 m; MHDOWG 2014; Table 1). However, in many estuaries the consumption of oxygen in the water column (pelagic BOD) has been found to be significantly higher than benthic BOD; this was identified as a significant knowledge gap in MHDOWG 2014. The report did however provide preliminary estimates of the total oxygen demand based on the expected inputs of organic carbon from farming, indicating that approximately two thirds of farm derived oxygen demand is likely to occur in the water column (Table 2).

More recently, Revill et al (2016) provided the first measurements of BOD in the Macquarie Harbour water column. The comparison between long term net drawdown and measured gross rates of oxygen consumption highlighted the role of surface exchange in maintaining oxygen levels above the halocline while extended periods without mixing lead to significant periods of low DO in the mid-water column. Oxygen drawdown was shown to vary markedly with depth for the period studied between October 2015 and January 2016 (e.g. Figure 14). At the Middle Harbour Gordon South site rates of net DO loss were quite low at the surface and increased ~ 3 times with depth peaking at 15m before falling again with increasing depth. Overall, although spatially variable water column BOD was estimated to be ~ 2 times benthic respiration, consistent with the estimates from MHDOWG (2014).

Table 1 Benthic BOD rates in the cage, buffer and control zones, with corresponding oxygen consumed and DIC produced for farm and non-farm areas (table from MHDOWG 2014; see report for detailed explanation of calculations).

Zone	Depth range	Area (km^2)		Oxygen consumption rate	Oxygen consumed		DIC produced	
	m	km^2	%	$\mu mol/m^2/hr$	tonnes /day	%	tonnes /day	%
Cage (farm)	15-25	0.17	2.3	900	0.341	4.9	1.27	12.6
	> 25	0.49		1500	0.190			
Buffer (farm)	15-25	0.44		350	0.432			
	> 25	1.61		750	0.245			
Control (non-farm)	15-25	53.91	97.7	240	9.937	95.1	8.84	87.4
	> 25	63.43		280	13.639			
Totals		120.05	100.0		24.784	100.0	10.11	100.0

Table 2 Estimated farm related BOD (tonnes per day) based on feed inputs in Macquarie Harbour for 2002-2013(table from MHDOWG 2014; see report for detailed explanation of calculations).

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
BOD	0.83	0.81	0.95	0.54	0.71	0.89	1.09	1.62	2.42	3.05	3.29	3.55

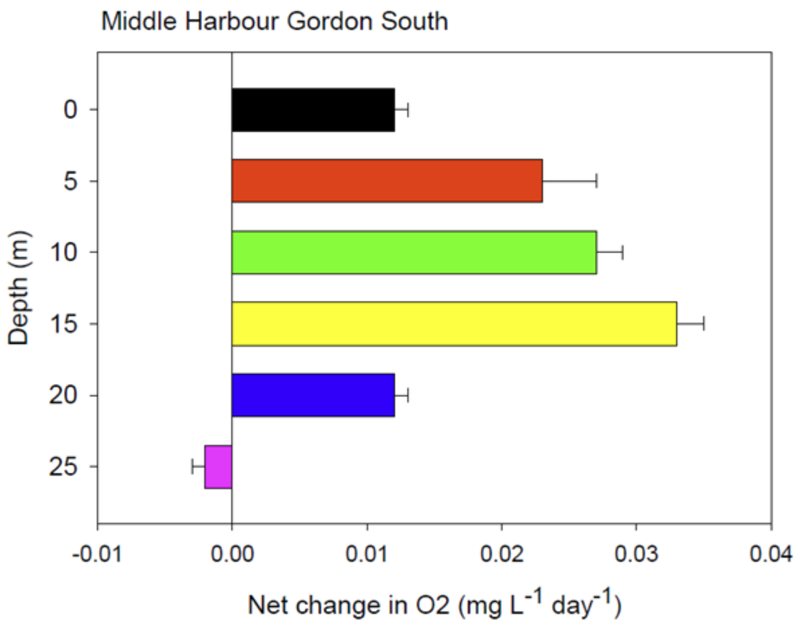
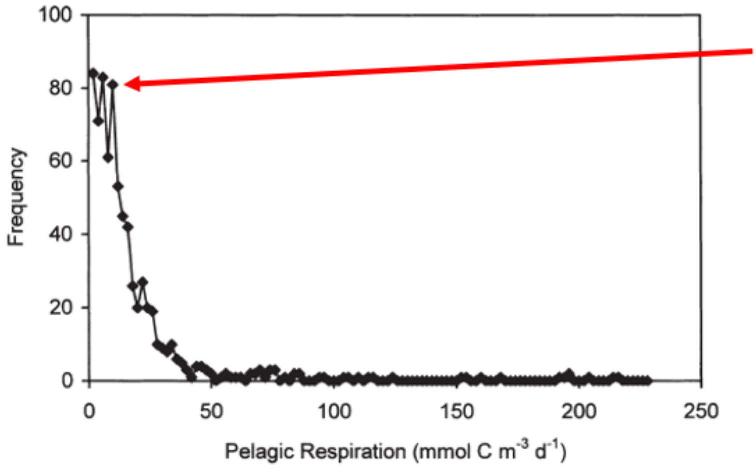


Figure 14 Summary plots of declines in oxygen concentrations at 6 depths at Middle Harbour Gordon (derived from linear regressions Data from Huon Aquaculture over the period 13/10/2015 to 05/01/2016). Figure from Revill et al. 2016.

In the context of rates of pelagic BOD measured in estuaries elsewhere in the world, the estimate of ~ 2.4mmol/m3/day is at the lower end (Figure 15). However, it is important to remember that the significance of this rate is dependent on the residence time (age) of the water mass; in Macquarie Harbour the residence time of middle and bottom waters will vary spatially and temporally, but is likely in the order of 100s of days. Thus, even low BOD will have a major effect on oxygen levels when the water is this old. Rates of pelagic BOD are also likely to vary substantially throughout the year with changes in temperature, river inputs and total farmed biomass/feed input rates.



Average of ~2.4 mmol/m^3/d was measured in December in Macquarie Harbour.
[mode in Hopkinson and Smith (2005) was 4 mmol/m^3/d]

Figure 8.6 Frequency distribution of individual pelagic respiration rates measured in 21 estuarine sites from around the world. While rates are presented as mmol C m^{-3} d^{-1}, original data were measured as *in vitro* oxygen consumption and converted to carbon equivalents either by the original author(s) or by us assuming an RQ of 1. The data (n = 707) follow a highly lognormal distribution, such that the arithmetic mean is 17.8 while the geometric mean is only 9.1.

From

Hopkinson, Jr. C.S., and Smith, E.M., 2005. Estuarine respiration: an overview of benthic, pelagic, and whole system respiration, In '*Respiration in Aquatic Ecosystems*' del Giorgio, P.A., and le B. Williams, P.J., [Eds.] Oxford University Press, USA, 326 pages.

Figure 15 Pelagic respiration rate estimated for Macquarie Harbour in the context for rates measured from estuaries around the world.

Oxygen resupply

In terms of the drivers of renewal, DO in Macquarie Harbour is mainly replenished through physical processes of (i) vertical mixing with higher DO surface waters; and (ii) higher DO ocean waters entering the Harbour over the sill and descending to "recharge" DO near the bottom (MHDOWG 2014). River discharge (volume and flow pattern) into Macquarie Harbour is identified as a significant factor influencing these processes, with other factors such as wind, tide and atmospheric pressure also important in regulating these events (Figure 16). The MHDOWG report suggests the most effective flow regime for maintaining stable DO renewal requires high flow variability that supports both frequent (surface-down) vertical mixing events (high river discharge) and frequent (bottom-up) recharge events (low river discharge). Over the period of DO decline the report characterises the flow regime as having relatively low variability with less frequent switching between the two renewal processes. The decline in bottom water salinities at the same time that DO has declined indicates that there has been a lack of oceanic recharge events within the Harbour (Aquadynamic Solutions 2015). The significant recharge of bottom waters observed in mid-2014 highlighted the importance of low atmospheric pressure combined with strong north-westerly (NW) winds (Figure 17). The strong NW winds appear to push surface water down towards the southern end of the Harbour or at the very least stops it from flowing out through Hells Gate. This may induce a slight gradient where water elevation at the southern end of the Harbour is higher than the northern end (also known as set up, though no measurements have been taken to support this). The rise in water elevation due to the low pressure system raises the water level outside of Hells Gate and inside the gate itself making it easier for oceanic water to flow across the sill and into the Harbour.

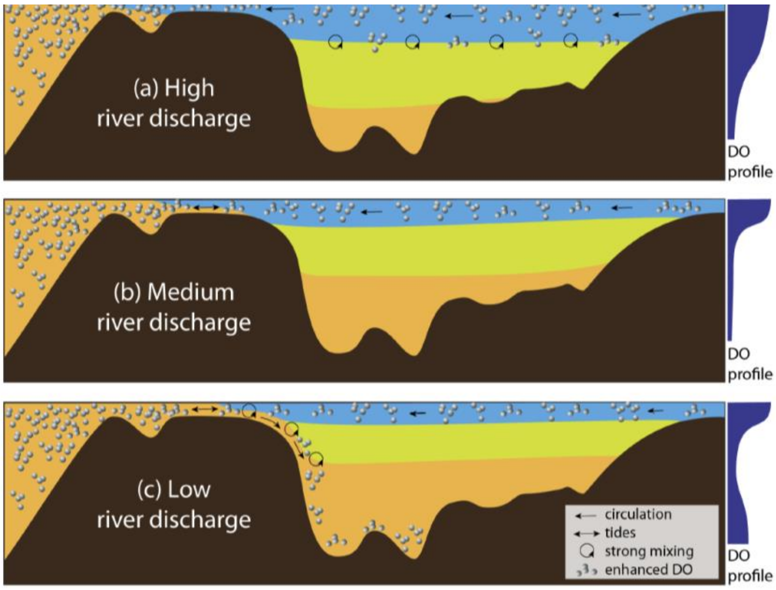


Figure 16 Schematic representation of physical processes operating in the Harbour under a range of river discharge conditions. Typical forms of the associated DO profiles are shown along the right hand side (figure from MHDOWG 2014).

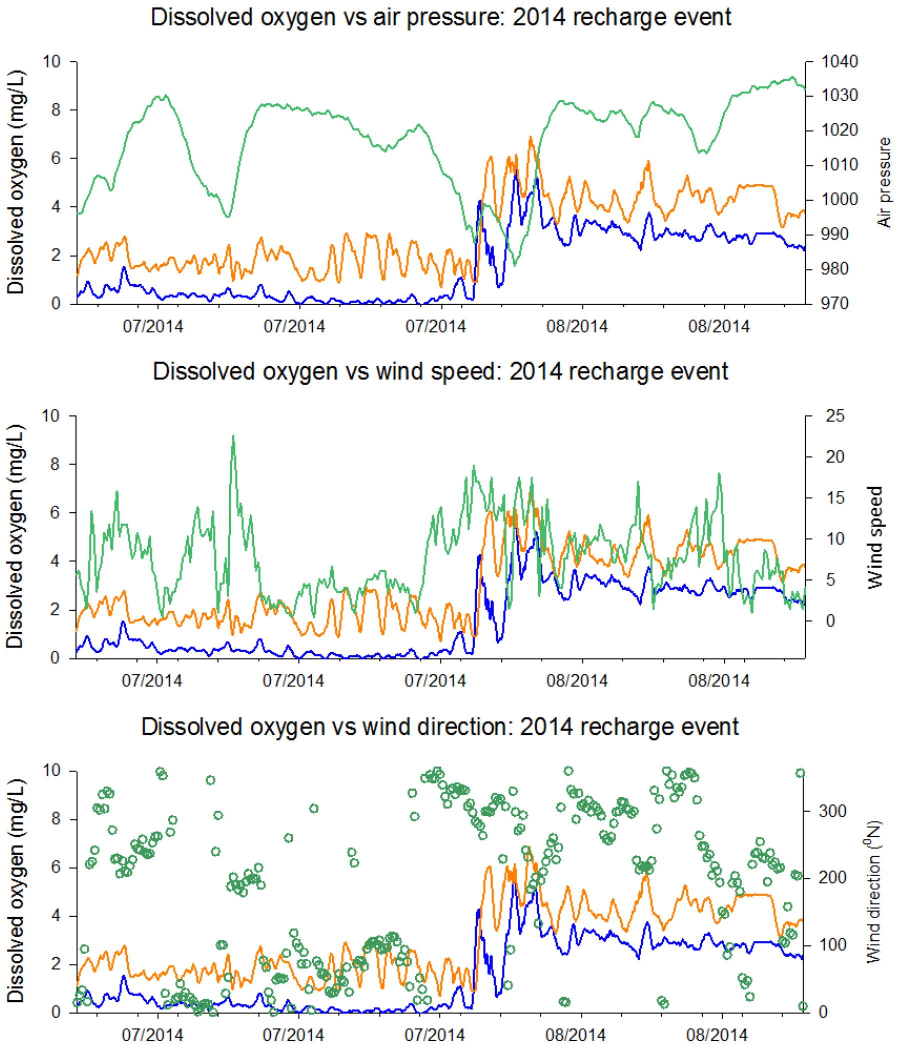


Figure 17 DO from loggers at 15 (orange) and 20m (blue) near Liberty Point versus air pressure (top), wind speed (middle) and wind direction (low) (all in green) during the August 2014 recharge event (from MHDOWG Update Report 2015).

Source and composition of particulate organic matter in the water column

The availability of labile organic matter and the presence of microbial organisms are fundamental to the processes that contribute to the consumption of oxygen in the water column e.g. aerobic respiration, nitrification. As part of ongoing work to understand the drivers of oxygen demand in the water column, the TSGA commissioned IMAS (Ross et al. 2016) to conduct a biomarker (C:N, isotopes, fatty acids and genomics) study to identify the source and composition of particulate organic matter, and the presence and abundance of the key microorganisms likely to be responsible for nitrification in the Macquarie Harbour water column.

A key finding from the fatty acid and genomic analyses was the significance of organic material produced internally in the Harbour water column via microbial production. This has important implications for our current understanding of carbon, nitrogen and oxygen dynamics in the Harbour. The prevalence of chemolithoautotrophs (nitrifying bacteria and archaea), that create organic matter using chemical rather than light energy, provides a new source of carbon that will lead to an oxygen demand when mineralised. In the case of these nitrifying organisms, ammonium is the source of energy used to fix carbon dioxide (CO_2), and the genomic results demonstrate that the distinct physiochemical gradients of Macquarie Harbour influence the distribution and abundance of these microorganisms. Bacterial nitrifiers were more common in the surface waters and ubiquitous throughout the water column compared to archaeal nitrifiers that were far more common at depth. Comparisons with nitrification rate measurements points to a more active role for the archaeal nitrifiers at depth, however, more work is required to confirm this relationship. Either way, the prevalence of nitrifiers in the water column, their conversion of ammonium to nitrate and consumption of oxygen clearly has direct implications for nitrogen cycling and oxygen dynamics.

The concentration of linoleic acid and oleic acid and their contribution to the fatty acid profile provided a clear signature of aquafeed waste in the environment, however, only in the cage itself. This is perhaps not that surprising when considering the highly diffusive nature of the water column, the relatively low stocking densities at the time of sampling and the difficulty in matching sampling with feeding and fish extraction. The study recommended future sampling focus on the peak stocking period in summer and in closer proximity to the cages (e.g. 0-100m) in order to provide greater sensitivity in determining the water column footprint of aquafeed waste.

Real time Dissolved Oxygen Data

The Sense-T Macquarie Harbour Salmon Project[2] is using sensing technology placed on 'sentinel' fish in pens and in the environment to collect real-time data on fish behaviour, water temperature, DO and depth.

The project is using VEMCO acoustic telemetered sensors (VEMCO, Nova Scotia, Canada), which measure pressure (range 0-102 m), temperature (range 0-25 °C) and

[2] Based at the University of Tasmania, Sense-T is a partnership between the University, CSIRO and the Tasmanian Government, and is also funded by the Australian Government. The Macquarie Harbour Salmon Project 'Salmon sentinels and sensor strings: real time environmental information and networking solutions to underpin a Decision Support System (DSS) for the Tasmanian salmon industry' is led by Dr Jayson M Semmens, Dr Kilian Stehfest, Dr Jeff Ross, Professor Chris Carter, Dr Jaime McAllister, Dr Adam Main, Mr Mick Hortle, Dr John McCulloch, Dr Karen Wild-Allen

DO (range 0-140 %) approximately simultaneously (within 250 milliseconds of one another) and transmit the resulting data together with the tags' ID coded as a series of acoustic pings (one ping series per environmental variable) which are recorded together with the date and time of transmission by an acoustic receiver. The sensors were placed on 'sentinel' fish in 2 pens on the Huon Aquaculture Strahan lease from December 2015 and March 2016 and on three environmental sensor strings on the edge of 3 leases along the central Harbour (December 2015 – present) (Figure 18).

Data from both the fish and environmental sensor strings can be viewed in real time on the dashboard provided by VEMCO and more recently via the Sense-T data portal (Figure 19). An example of the data accessed from a tag, in this case from one of the environmental strings, can be seen in Figure 20. A more detailed presentation and discussion of the environmental string data is provided in the following section describing the current status of the Harbour environment. Other key elements of the Sense-T Salmon Project include the deployment of CSIRO's environmental profiler that routinely profiles the full water column for key environmental parameters transmitting the data back live to the Sense-T data portal. Importantly this data is being used to help calibrate and validate a near real time hydrodynamic model (including DO as a tracer) of the Harbour by CSIRO.

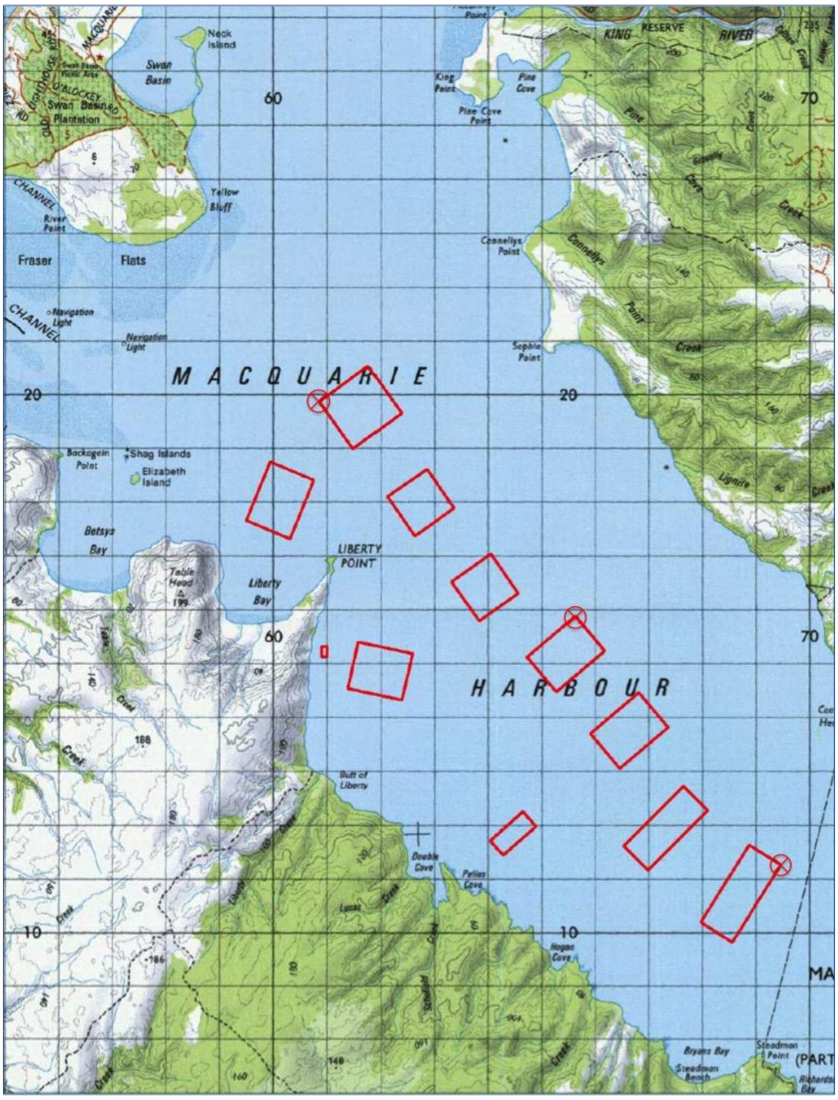


Figure 18 Map of Macquarie Harbour showing the location of the 3 environmental sensor strings (red circle with cross) on the edge of 3 leases along the central Harbour.

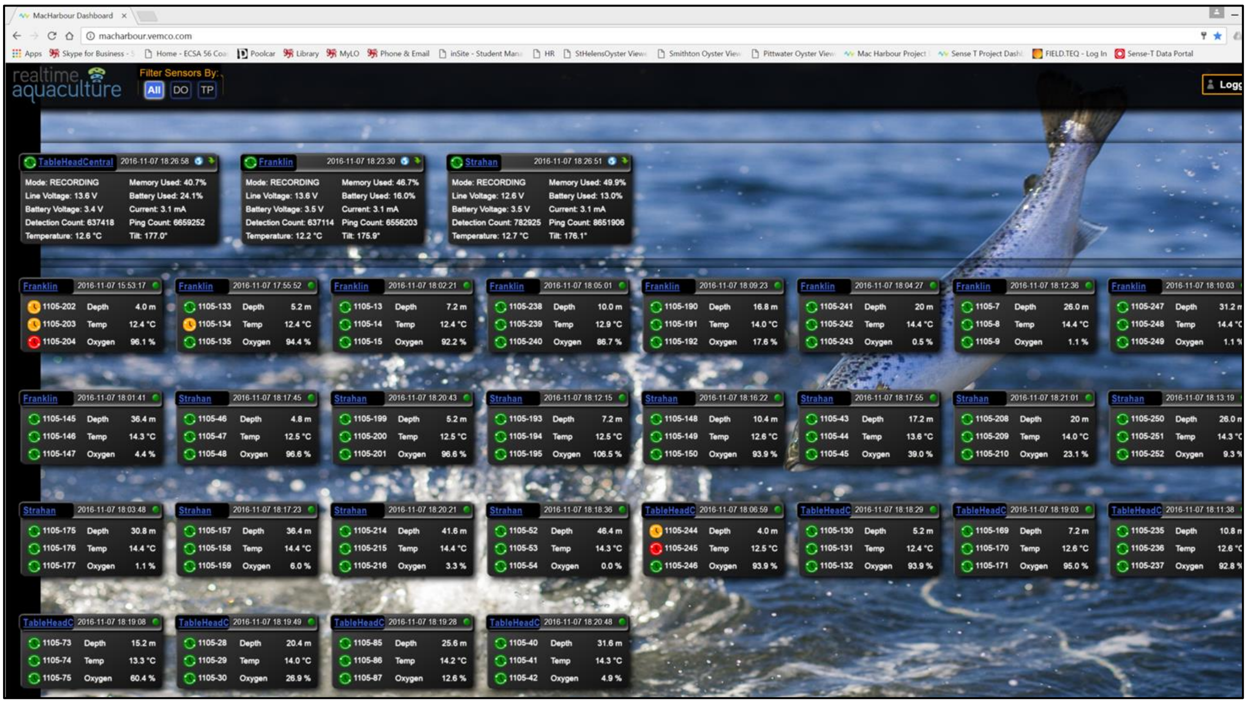


Figure 19 The VEMCO dashboard (top) where real time fish and environment tag data can be accessed and the Sense-T data portal where real time data can also be accessed.

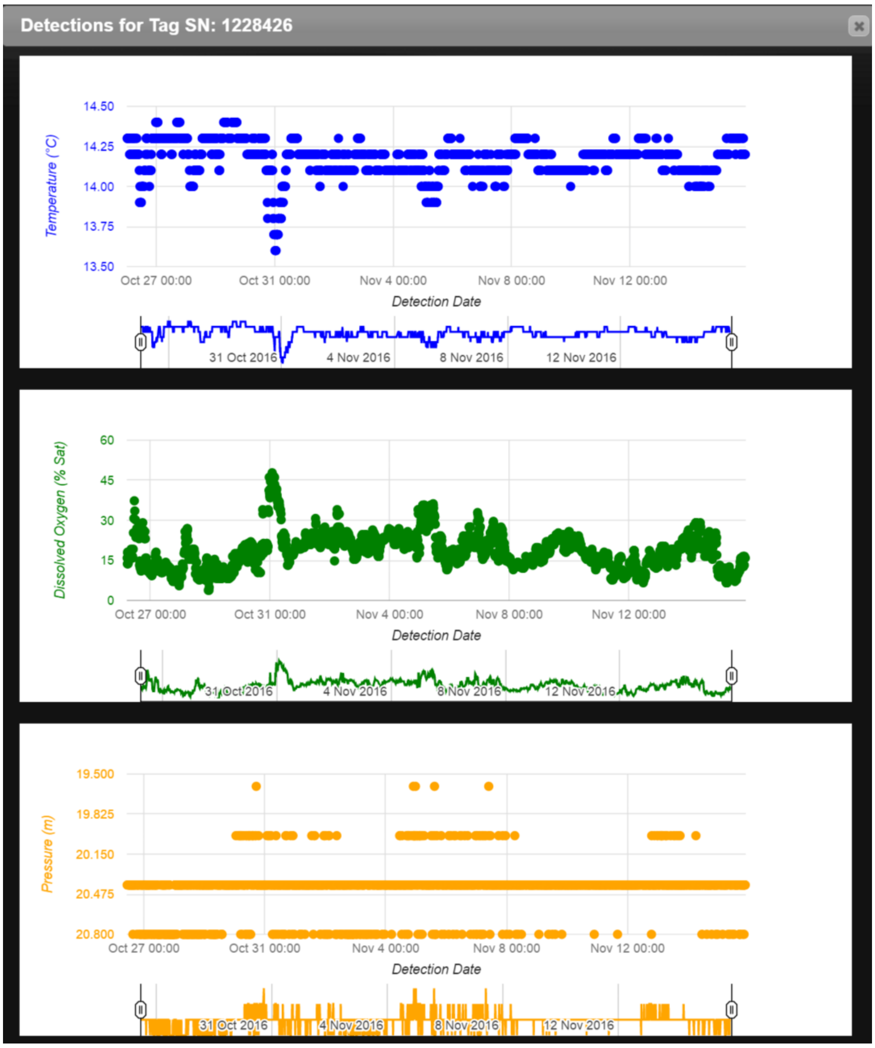


Figure 20 screen shot of the data accessed for one of the environmental tags on the VEMCO dashboard.

The December 2015– March 2016 deployment on 'sentinel' fish coincided with one of the hottest summers on record in Tasmania (BOM 2016). Combined with an extended period of calm weather (i.e. limited wind induced mixing and aeration of surface waters) and low rainfall and runoff into the Harbour, this provided the opportunity to examine the behavioural response of salmon to seasonal extremes of DO and temperature. The results of this study will be available via publication in a peer reviewed journal, but in brief salmon were found to actively avoid both low DO levels near the bottom of the aquaculture cage and warm surface temperatures, rather than positioning themselves based only on their optimal temperature as was previously thought (Figure 21). This led to a considerable contraction in the vertical habitat available to them. Despite the avoidance behaviour, fish spent a large amount of time in waters with suboptimal DO levels (<60 % saturation; Figure 22), suggesting that the hypoxia tolerance in the Tasmanian population might be higher than that reported for other stocks.

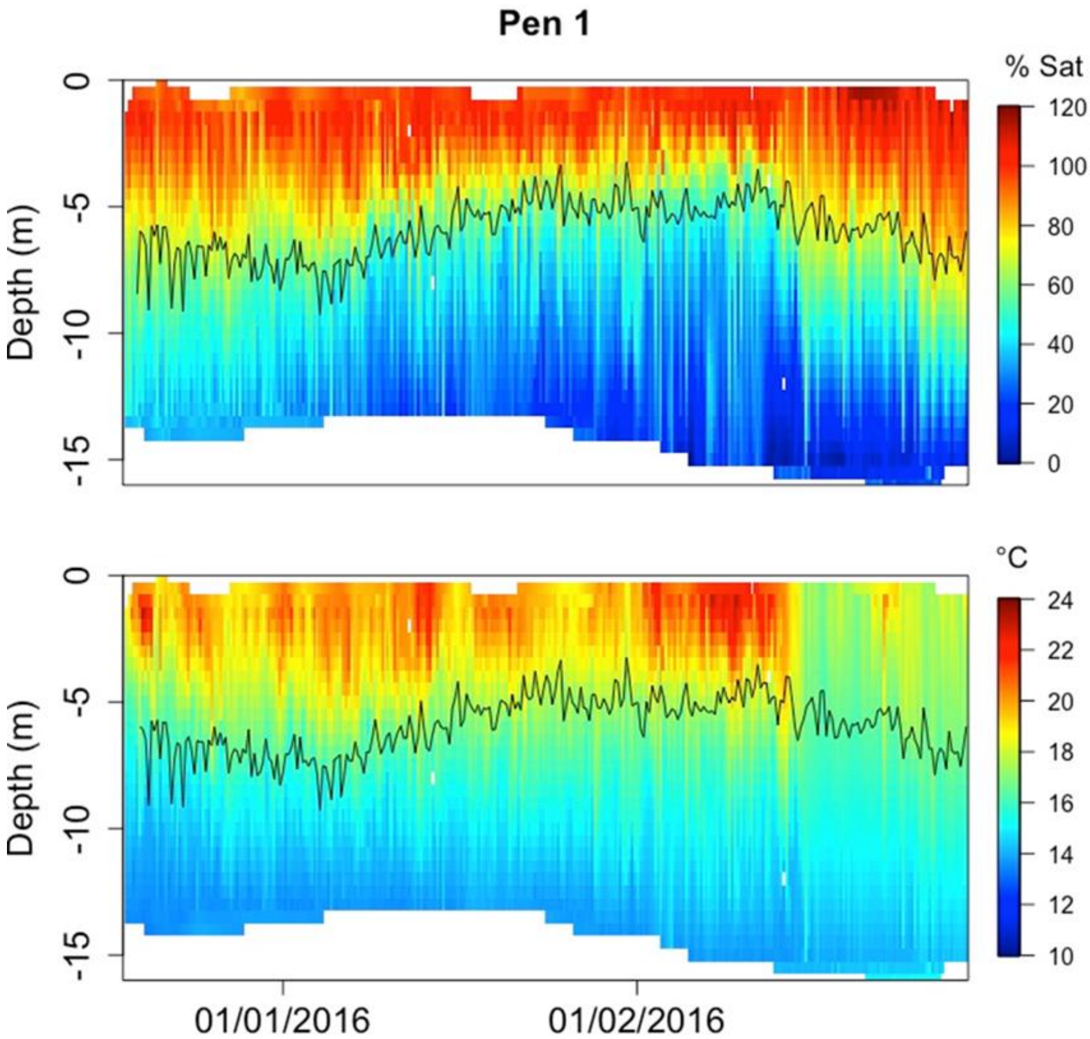


Figure 21 Profile of DO and temperature in experimental cage 1 during the study period. Black line indicates mean swimming depth averaged over all tagged fish in cage 1.

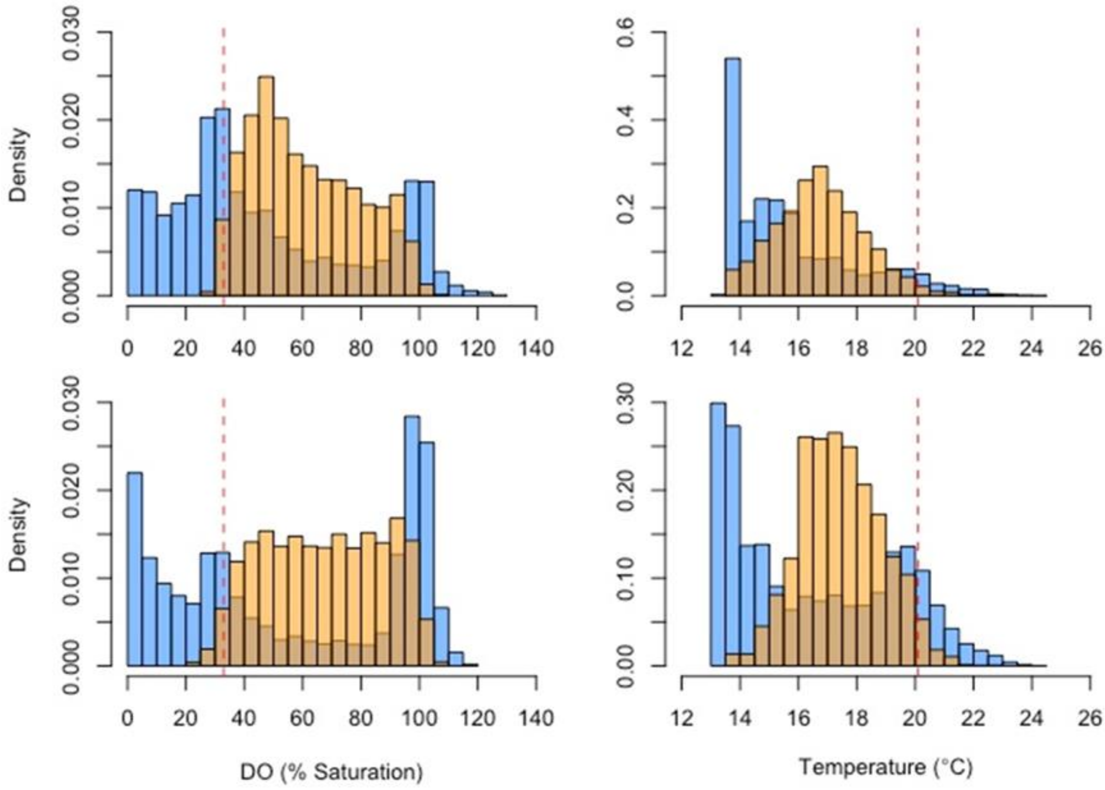


Figure 22 Distribution of DO and temperature values experienced by the fish (orange) and measured throughout the cage water column (blue) in the two experimental cages (Data from cage 1 shown in the top panel, data from cage 2 shown in the bottom panel). Vertical dashed lines indicate the 35 % DO saturation threshold in the DO distributions and the mean and 97.5 centile in the temperature distributions. To account for the fact that some stationary string tags malfunctioned during parts of the study period, water column data were grouped into 2.5 m depth bins and each data point weighted by the inverse of the total number of observations for its depth bin for the computation of density distributions.

CURRENT STATUS

Oxygen levels

In mid-2014 there was some respite from the steady decline in bottom water DO levels that had been occurring since 2009 (Figure 23). However, DO levels were and still remain well below the levels recorded between 1993 and 2009 (Figure 23). DO levels are now extremely low throughout the Harbour, but most notably in the southern part of the Harbour. All of the independent data sets (industry, EPA, Sense-T, Parks, IMAS and CSIRO) are providing the same picture; DO levels in bottom waters are now worryingly low.

The monthly monitoring data provides valuable insight into the long term trends in DO levels, but the increasing frequency of data collection associated with the daily profiling and continuous data loggers has provided a detailed insight into the evolution of DO levels throughout the Harbour. This is best seen in the contour plots produced from the Sense-T environmental strings that provide real time data on DO and temperature throughout the water column at 3 sites along the centre of the Harbour; Table Head closest to the influence of the ocean, Franklin the most southern site nearing the boundary of the World Heritage Area (WHA), and Strahan, a site midway between the two (Figure 24).

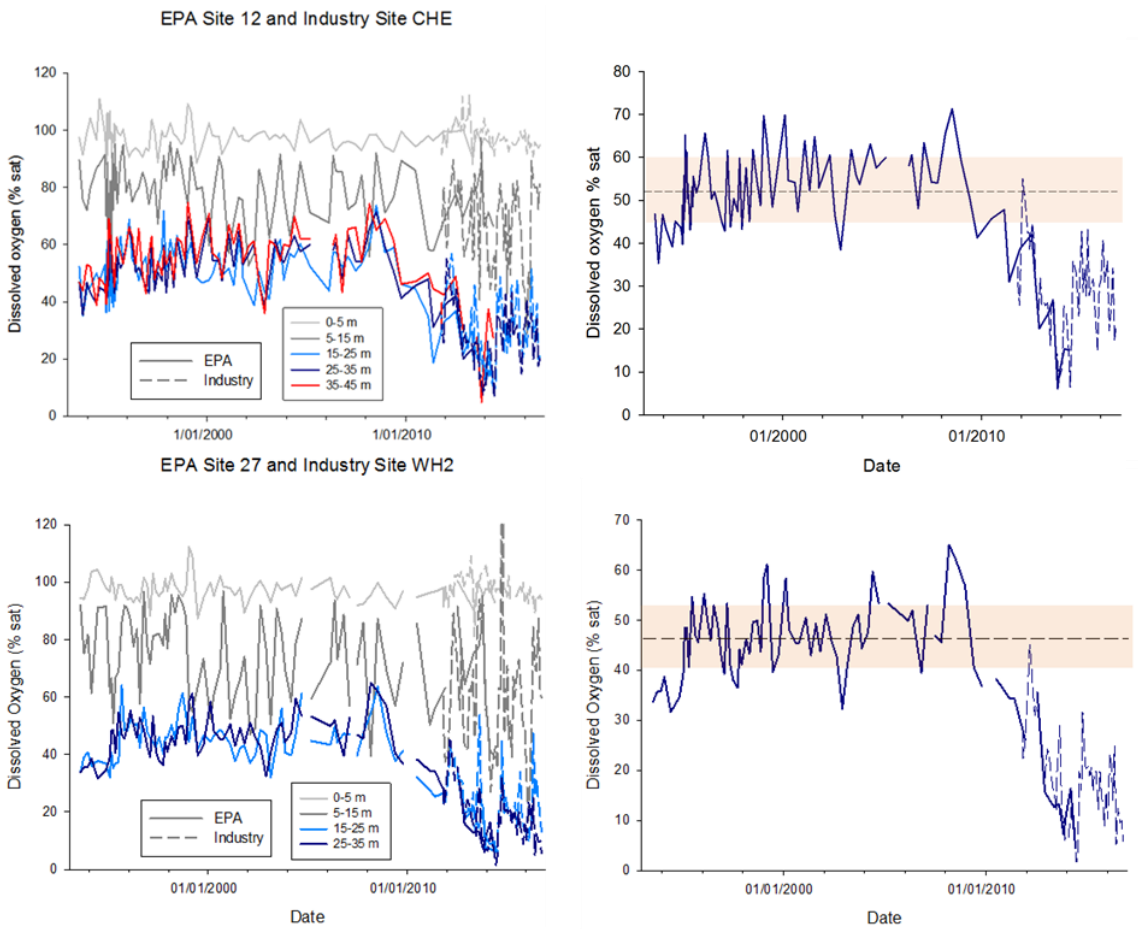


Figure 23 DO (% saturation) level from two long term EPA monitoring sites, 12 and 27. Industry data for the past 5 years from sites closest to the EPA are also shown for comparison. These sites/data have been shown to be comparable in previous studies (MHDOWG 2014). The plots on the left show the data at different depths whilst those on the right are only for 25-35m, and show the median (dashed line) and the 20th and 80th percentiles (shaded area), calculated from data collected between 1993-2009.

At the Franklin site DO levels are now less than 10% saturation (i.e. less than 1 mg l^{-1}) at all depths below 20m, and loggers are now frequently recording 0% saturation. At Strahan and Table Head levels are consistently below 20% saturation (less than 2 mg l^{-1}) (Figure 24). From the data shown in Figure 24 it is clear that these low DO levels (i.e. less than 10% below 20m) are becoming more common at the Strahan site in the mid-Harbour, and that levels at Table Head (near the mouth of the Harbour) have declined and are now also markedly lower below 20m. Proximity to the influence of the ocean and the concurrent effects of bottom water residence time (i.e. the fact that the bottom water is likely to be resident in the system for a longer period of time further from the entrance to the ocean) are likely to be important in determining the oxygen levels at the respective sites.

Risks to the ecology

The levels of DO now observed in bottom waters throughout the Harbour present a significant potential risk to the ecology of the Harbour. In October 2016, IMAS conducted a benthic survey of 4 leases and a number of Harbour wide external sites as part of ongoing research in FRDC Project 2015/024 (Managing ecosystem interactions across differing environments: building flexibility and risk assurance into environmental management strategies). This represents the 6th survey since January 2015, the first two of which were completed under FRDC 2014/038 and have been reported in Ross et al. (2016). It is clear from the latest data that there has

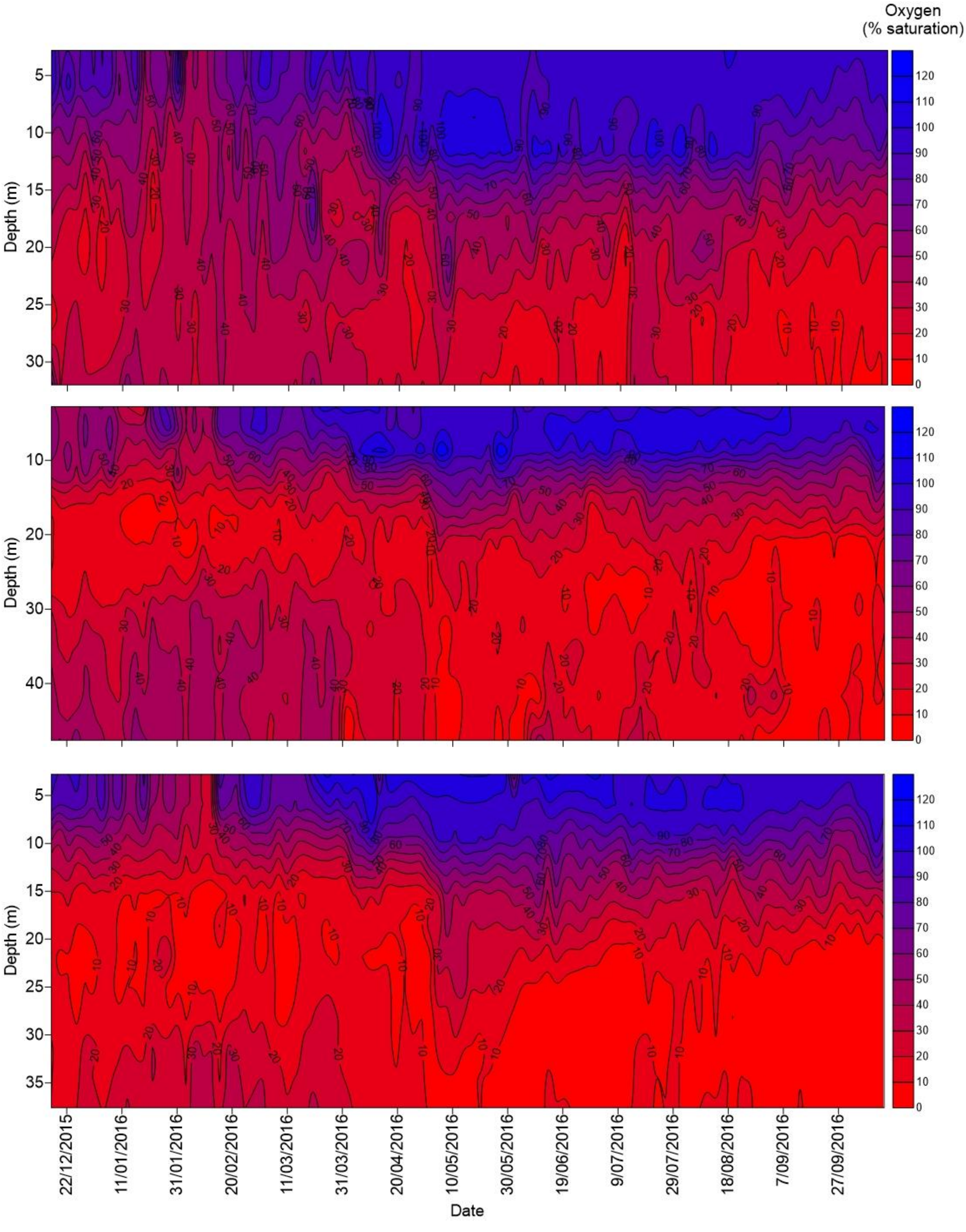


Figure 24. Contour plots showing DO profiles through the water column from the environmental strings at Table Head (top panel), Strahan (middle panel) and Franklin (bottom panel) over the period from December 2015 to date (October 2016). NB see Figure 18 for map of string locations. It is important to keep in mind that the Sense-T project is about demonstrating the 'proof of concept' with the sensor deployment and although the data from the sensors has been periodically checked the next stage of the project will involve a more rigorous QA/QC process. However, that said, the calibration checks and consistency with other independent data sets (EPA, Parks, Industry, CSIRO, IMAS) from the Harbour does provide a degree of confidence in the both the levels observed and the overall response patterns.

been a significant decline in the total abundance and number of species collected from the benthic infauna at all of the leases assessed in the most recent survey (Figure 25). However, the magnitude of this change varied across leases; with the effect increasing with distance from the Harbour entrance (Table 3). At lease 1, the data suggests that the sediments are virtually devoid of fauna out to at least 500m from the cages (Figure 25). At leases 2 and 3 there has also been a significant decline in both total abundance and the number of species collected in grab samples out to at least 500m (Figure 25). At lease 1 there was an average of ~556 individuals per m^2 and ~4 species a grab present across the previous 5 surveys, whilst at leases 2 and 3, the change in abundance and number of species between survey 6 and the previous surveys reflects a five-fold decline from an average of ~878 and 839 individuals per m^2 and ~7 and 4 species per grab to ~171 and 145 individuals per m^2 and only 3 and 2 species per grab respectively (Table 3). The decline in faunal abundance and number of species was also observed at lease 4, although at this lease the reduction was less severe, dropping from an average of ~1088 individuals per m^2 and ~7 species per grab in the first 5 surveys to ~372 individuals per m^2 and ~5 species per grab in survey 6. This is a reduction of ~66% in abundance and ~37% in the number of species at this lease (Table 3).

The reduction in faunal abundance and number of species was also apparent at the external sites where, as with the lease areas, the greatest changes occurred at sites in the southern end and the middle of the Harbour (Table 3, Figure 27). At site 39, closest to the world heritage area, total abundance and the number of species was reduced by 97% and 92% respectively in survey 6 when compared to surveys 1-5 (Table 3), as compared with a reduction of 35% and 11% in abundance and the number of species at the site closest to the Harbour entrance.

When compared with previous surveys the data from the most recent sampling also provides compelling insight into the likely influence of bottom water oxygen concentrations on the benthic response (Figure 26). In the previous surveys there was quite a bit of variability in bottom water DO levels; lease 1 in particular often experiencing bottom DO of ~ 1 mg l^{-1}. In February 2016 the bottom water DO levels stand out as being much higher, and this can also be seen in the Sense-T contour plots (Figure 24). This has yet to be explored in detail, but there is evidence of a significant oceanic recharge of bottom waters in late 2015/16 when river flows were very low. A combination of a shallow halocline, low winds and a marine heat wave saw the low DO waters in the middle of the water column encroaching on the surface in late summer; with the newer more oxygenated water lying underneath. The return of strong river flows, a deeper halocline and windier conditions in autumn appears to have pushed the low DO mid waters deeper, mixing with the bottom waters, which when combined with the additional drawn down potential of sediment and water column BOD, has seen the bottom water DO levels reach the critically low levels currently observed. It is also likely that this increase in river inflows may have pushed the lower DO water in the southern end of the Harbour (where residence times are greatest) further north. In the most recent survey (October 2016) DO concentrations declined to less than 1 mg l^{-1} at all leases, with average concentrations across the transects of 0.28, 0.45, 0.57 and 0.8 mg l^{-1} at leases 1, 2, 3 and 4 respectively (Figure 26).

Whilst it is difficult to say for certain what the ecological effect of this might be, there have been a number of studies into the potential effects of hypoxia that can help provide some insight. A recent study by Riedel et al. (2014) on the influence of

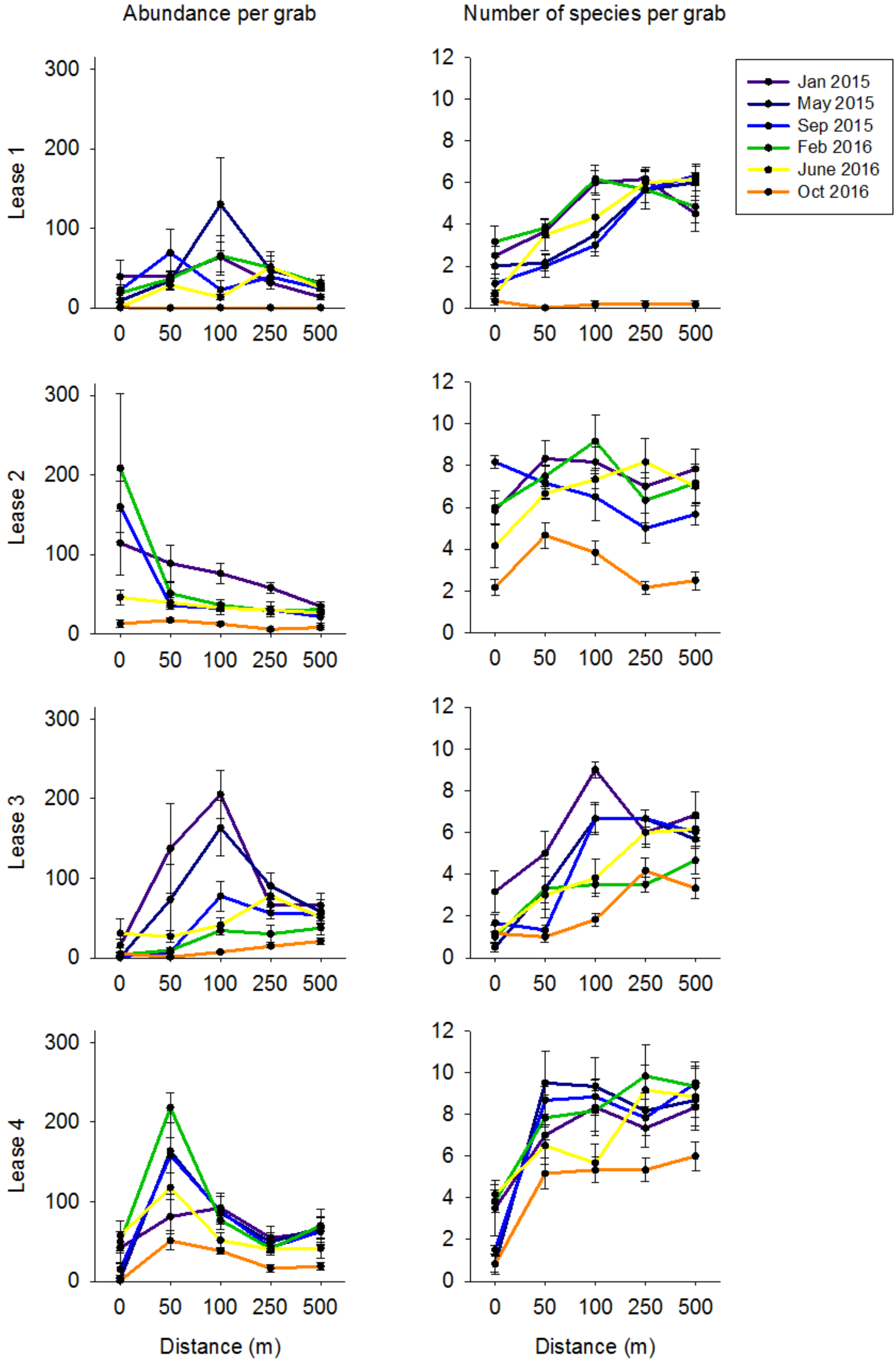


Figure 25 Plots of total infaunal (>1mm) abundance (per grab = ~0.0675m²) and number of species collected in grabs (n=3) at 0, 50, 100, 250 and 500m from cages at 4 leases in Macquarie Harbour from surveys between January 2015 and October 2016. The data for each lease represents the mean (±SE) from two transects that radiate out from cages on opposite sides of the lease. Lease 2 was not surveyed in May 2015.

Table 3 Average abundance/m² and number of species/grab for leases 1-4 and external sites. Both leases (prefaced with L) and external sites (prefaced with E) are listed in geographical order from the river end to the Harbour mouth highlighting the concomitant gradient in observed changes in species and faunal abundance.

Lease/External Site	Average abundance/m² Surveys 1-5	Average abundance/m² Survey 6	% change	Average no. of species/grab surveys 1-5	Average no. of species/grab survey 6	% change
L1	556.74	2.47	**99.56%**	4.19	0.17	**96.02%**
L2	878.39	170.86	**80.55%**	6.96	3.07	**55.93%**
L3	839.21	145.19	**82.70%**	4.45	2.30	**48.35%**
L4	1087.60	372.84	**65.72%**	7.23	4.53	**37.27%**
E39	180.74	4.94	**97.27%**	4.20	0.33	**92.06%**
E41	39.51	9.88	**75.00%**	1.80	0.67	**62.96%**
E26	29.63	9.88	**66.67%**	1.50	0.67	**55.56%**
E21	149.14	79.01	**47.02%**	3.33	1.67	**50.00%**
E16	112.59	34.57	**69.30%**	4.53	2.00	**55.88%**
E11	534.32	237.04	**55.64%**	8.47	6.67	**21.26%**
E49	745.68	483.95	**35.10%**	12.40	11.00	**11.29%**

River ↓ Mouth

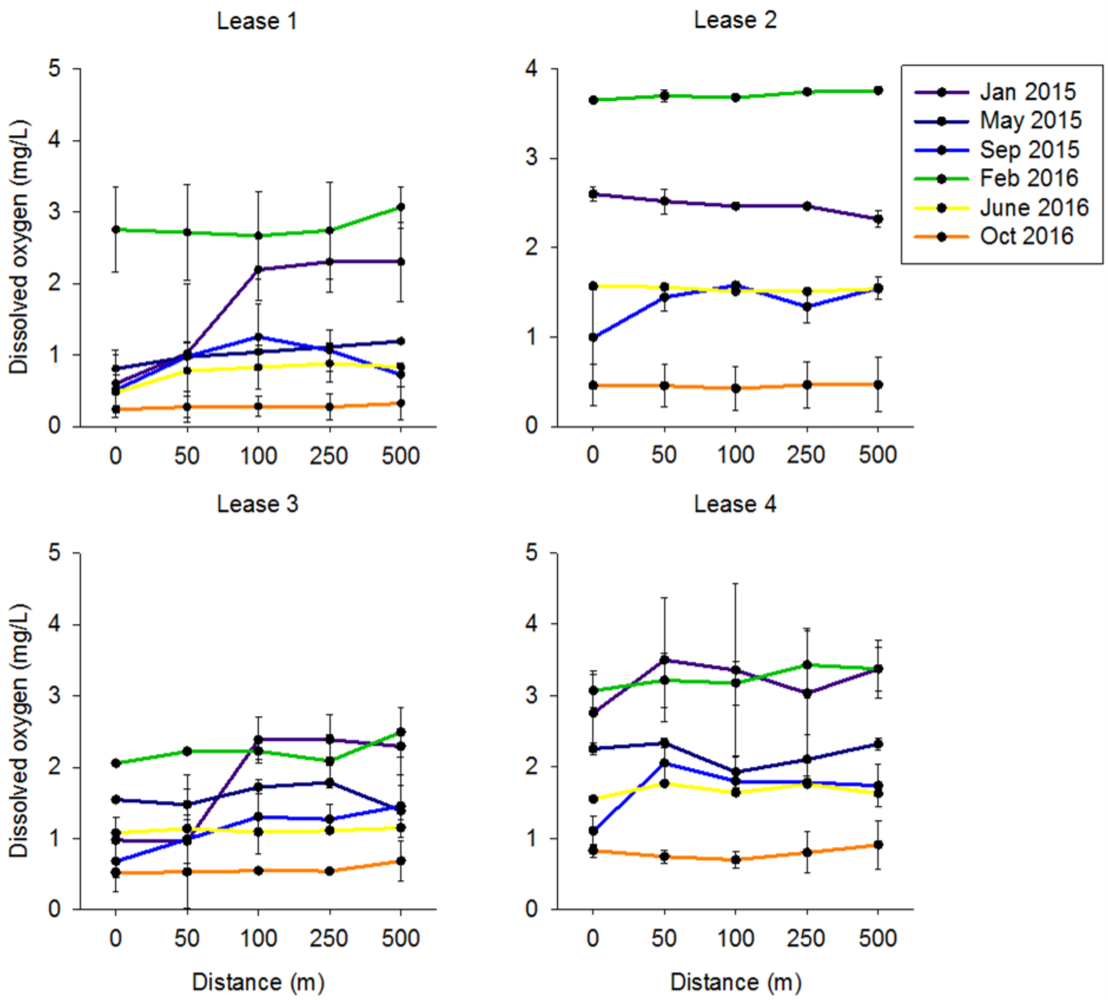


Figure 26 Bottom water DO concentrations (mg/L) measured at 0, 50, 100, 250 and 500m from cages at 4 leases in Macquarie Harbour from surveys between January 2015 and October 2016. The data for each lease represents the mean (±SE) from two transects that radiate out from cages on opposite sides of the lease. At lease 1, the depths of the transects are different (27-30m vs 35-38m) and hence the increased variation in the data. However, for the purpose of this plot, the change in DO levels between surveys remains evident despite the different depths of the transects. Note, profiles weren't done at lease 2 in May 15 and only one transect was profiled in June 2016.

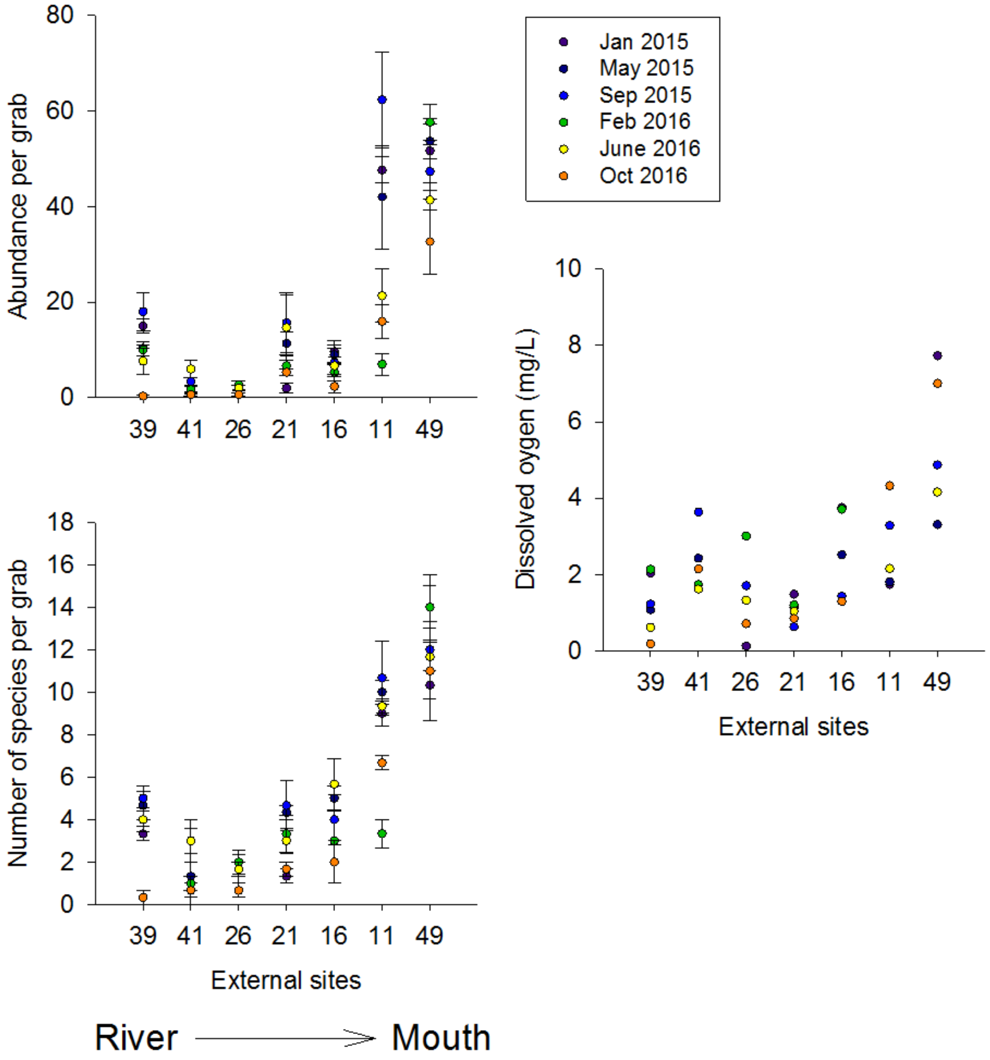


Figure 27 Plots of total infaunal (>1mm) abundance (per grab = ~0.0675m²), number of species collected in grabs (n=3) and DO in bottom waters at 7 external sites in Macquarie Harbour from surveys between January 2015 and October 2016. The data for each lease represents the mean (±SE) from three replicate grabs. Note, site 26 was not surveyed in May 2015.

hypoxia and anoxia on invertebrate behaviour showed that behavioural effects can be observed under mild hypoxia, with mortality increasing under moderate (0.5 – 1 mg l^{-1}) to severe hypoxia (< 0.5 mg l^{-1}), particularly during longer exposure times (Figure 28). Given that the benthos in Macquarie Harbour are exposed to similar levels, then the levels of mortality observed are not surprising. Vaquer-Sunyer & Duarte (2008) investigated thresholds of hypoxia for marine biodiversity, highlighting marked differences in sensitivity across taxa (see Figure 30). The study also shows that very small changes in DO, particularly at low levels, can have a major effect on the ecological response – this is particularly relevant to the levels of DO currently seen in Macquarie Harbour, suggesting that even slight declines/ improvements where levels are so low can have quite marked consequences. The VEMCO Aquaculture dashboard shows that the DO levels as measured by one of the Sense-T environmental sensors reflect very low oxygen levels (i.e. severe hypoxia/anoxia) over an ever increasing period of time; this might explain the observed benthic responses (Figure 29). Interestingly, Vaquer-Sunyer & Duarte (2010) also demonstrated that survival times under hypoxia can be further reduced by ~ 30% when also exposed to hydrogen sulphide (H_2S), with the effects on survival under such circumstances being more pronounced for eggs than for juvenile and adult stages. This would have particular significance for any fauna within the Harbour where aspects of their life history or behaviour might result in them being exposed to the hypoxic bottom waters, for example where either reproductive strategy or foraging occurs in these regions. An increase in hypoxia within the bottom waters could also affect the ecological processes underpinning organic matter processing and sediment recovery, as recruitment to the sediments occurs both through larval transport and migration from surrounding areas and severe hypoxia has the potential to limit that recruitment.

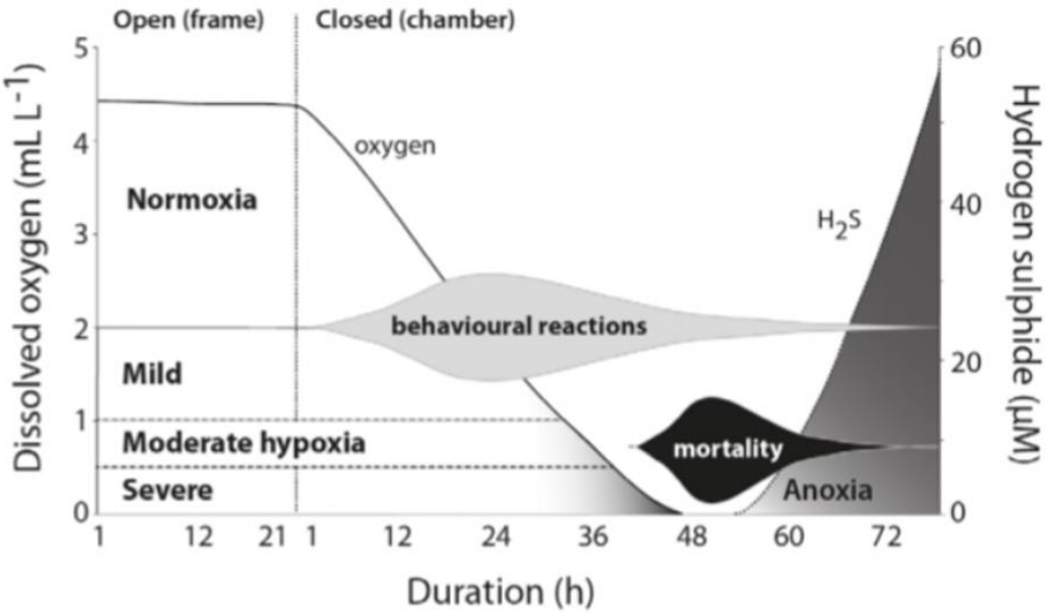


Figure 28 Schematic diagram reproduced with permission from Riedel at al. (2014) highlighting the effects of DO concentrations and exposure duration on behaviour and mortality.

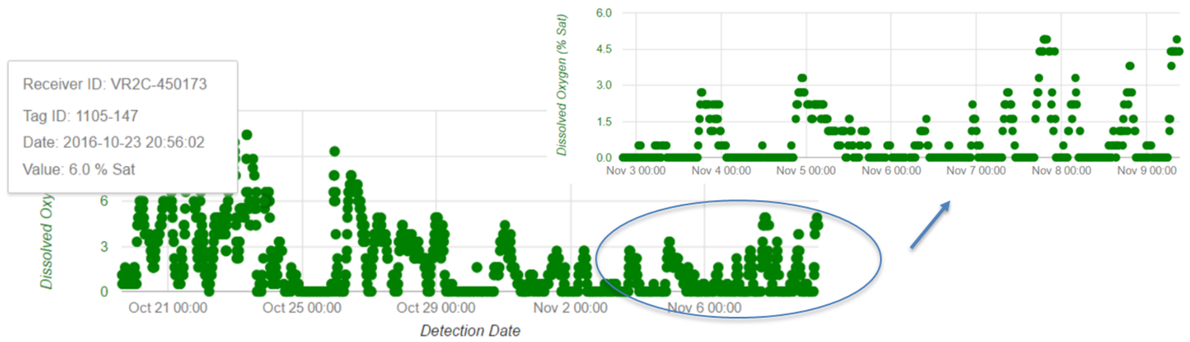


Figure 29 Screen shot from the VEMCO Aquaculture dashboard showing data from one of the Sense-T environmental sensors in bottom waters.

Benthic response to organic enrichment – multiple scales?

Whilst the results to date suggest that the pattern of benthic response to organic enrichment is consistent with that defined by Pearson and Rosenberg (1978) (Figure 31) and is in line with our understanding and management from SE Tasmania, the scale and extent of effects may be much greater than originally anticipated. The data clearly show that the benthic community has been highly enriched close to cages/ leases; with *Beggiatoa* and low diversity communities at the most impacted sites, transitioning to an area dominated by opportunists and then slowly recovering with distance from the enrichment source (Figure 31). This pattern was clearly evident around the cages in the initial studies (e.g. Figure 9, 10 & 11), but this spatial

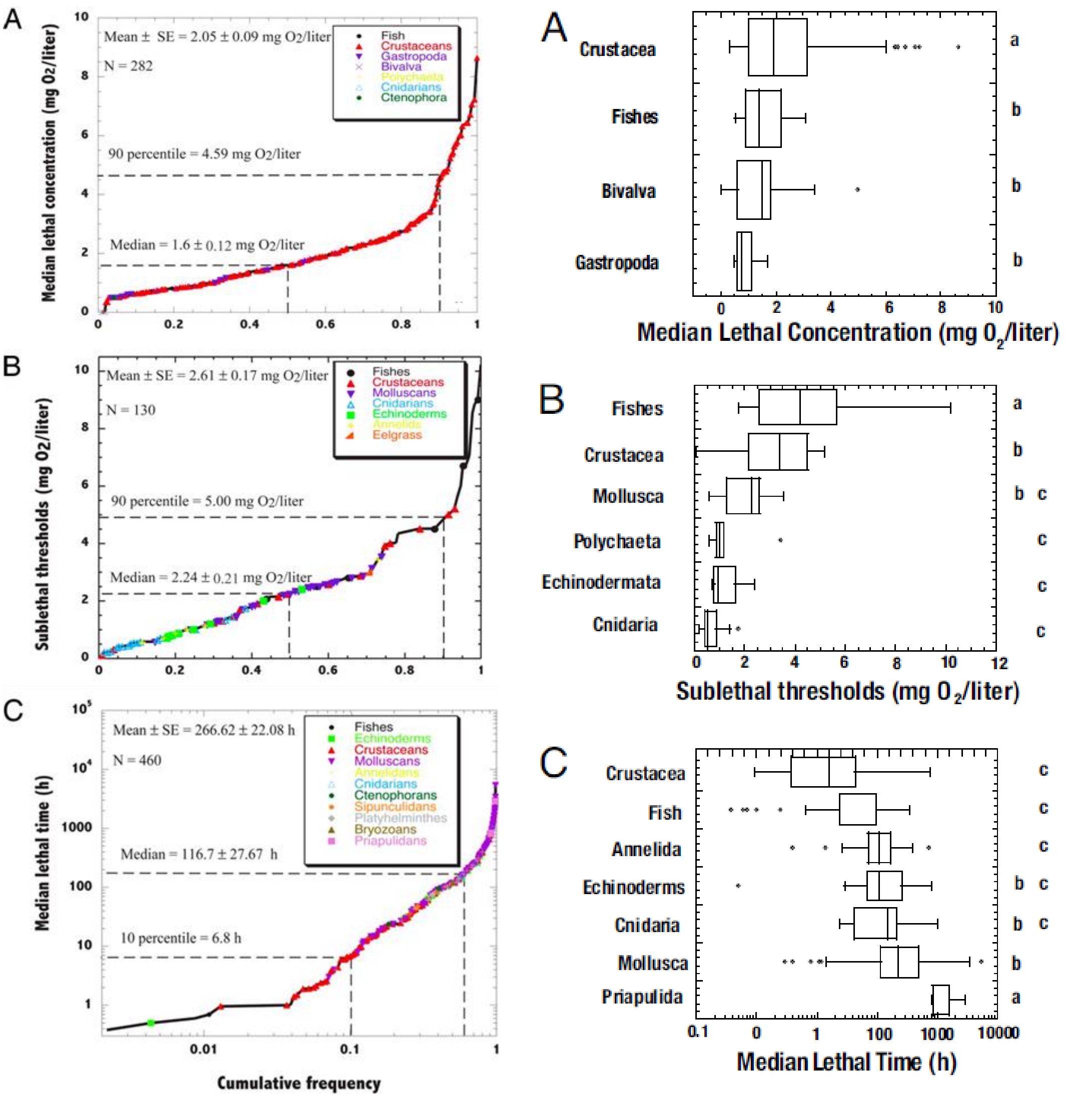


Figure 30 Cumulative distribution of median lethal concentrations, sublethal thresholds and lethal time for marine benthic communities (left panels) and box plots showing the distributions of oxygen thresholds among taxa– figures reproduced with permission from Vaquer-Sunyer & Duarte (2008).

response pattern (footprint) appears to have extended in the most recent survey; such that the area of influence may now reflect the effects of the whole lease rather than individual cages (Figure 25). However, given that changes have also been observed at the external sites it is difficult to untangle potential lease effects from those occurring more broadly in the Harbour in response to the low DO concentrations. In addition, the level of impact associated within the whole lease may also be changing temporally, along a trajectory similar to that described in Figure 31 – i.e. changing from a naturally depauperate community (as described in the baseline before farming) to a moderately impacted community defined by opportunists (consistent with what we might expect to see after the first few years of farming (surveys 1-5)), to a much more degraded “depauperate” community observed in survey 6. Again, the concurrent decline at some of the external sites in the most recent survey makes it difficult to discern specific lease effects. However, the fact that we appear to be seeing ‘Harbour’ scale change is a concern, and is something that may need to be considered in any ongoing management strategies of the Harbour. In Figure 32, it is clear that infaunal abundance in the Harbour was markedly higher in 2015 and 2016 compared with the baselines in 2000, which leads to the possibility that the whole Harbour may be (or be in the process of) transitioning along that enrichment gradient.

The one positive aspect of identifying that the ecological response follows the expected successional pattern of degradation/ recovery (Ross et al., 2016) is that this provides some reassurance that if we can manage to get the sediments “on the road to recovery” it should theoretically be possible to rehabilitate them. However, there are two key confounding factors that could hinder such recovery; (i) the fact that the sediments are already highly degraded in some areas, and (ii) that the overlying bottom water DO is also very low. These factors will make the remediation process more difficult. In other farming regions the bottom waters would normally have higher oxygen levels than the sediments and this allows both passive and active (i.e. via bio-irrigation) replenishment of oxygen into the sediments, but where the overlying water is oxygen depleted there may be little “room to move” in terms of sediment recovery. Under these conditions it is increasingly difficult to predict how the sediments might respond to farm management (e.g. fallowing) and the concern is that they may not be able to sustain repeat farming in the same way as other growing regions.

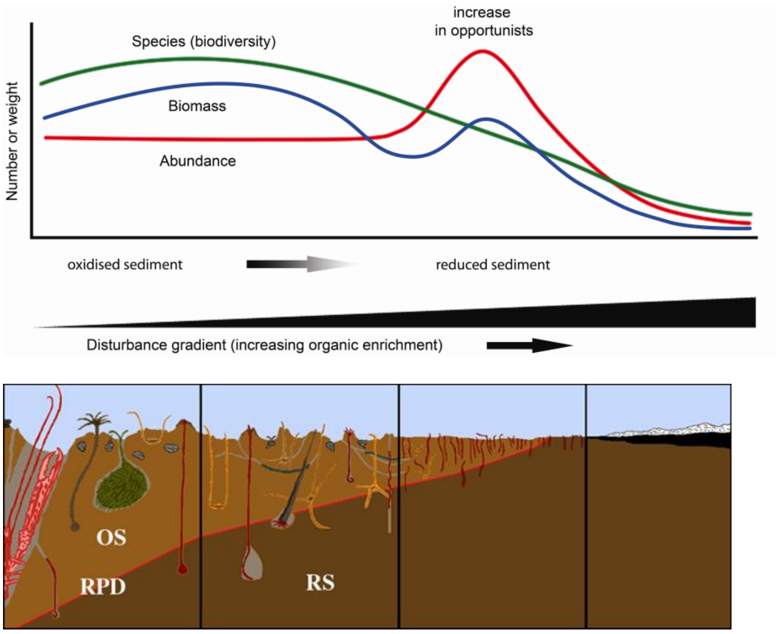


Figure 31 The Pearson and Rosenberg (1978) model of benthic response to organic enrichment (OS= oxic sediment, RS = reduced sediment, RPD = Redox potential discontinuity).

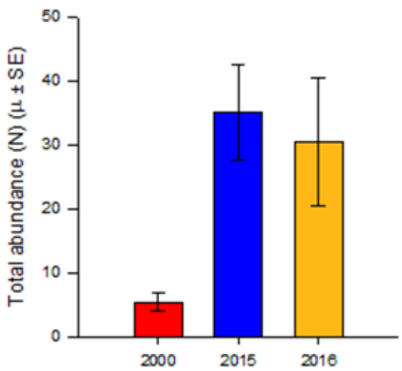


Figure 32 Mean (per grab) total abundance of all taxa at external sites in 2000, 2015 and 2016. Values are means, error bars indicate standard error.

Water Column Condition

Clearly there is an urgent need to better understand in detail the spatial extent of low DO bottom waters in the Harbour and the factors (physical and biological) that might affect those DO levels.

KEY QUESTIONS/ ISSUES:

- **What is the nature of the low DO water mass?**
  Do we have 2 or more separate 'halos' of depleted DO water in the central basin or is there a single hypoxic water body that runs along the bottom of the Harbour from the heads to the WHA?
  Proposed Research
  Deployment of sensors to monitor both the condition of the water body (environmental sensors) and the water movement within the system (ADCP current loggers) would inform this issue. In addition, deployment of gliders/ autonomous underwater vehicles (AUV) could deliver a more detailed spatial characterisation of DO throughout the Harbour – this would provide invaluable data on the DO conditions in areas outside the main farming areas. The continuous nature of the Sense-T data collected thus far has provided greater insight into pelagic O2 dynamics than the data collected monthly, consequently it is recommended that the continuous monitoring be maintained and extended to include both additional sensor strings and sites.

- **Does farming influence water column DO levels within the Harbour as a whole, and if so what does this mean for sustainable farming?**
  Whilst it is clear that farming can affect the DO levels within and under cages, it is not currently clear to what extent individual farms contribute to the low DO water body (bodies) in the broader Harbour, or whether this low oxygen water mass contributes to deterioration of the environmental and sediment conditions under/ around farms.
  Proposed Research
  To understand this we need further information on pelagic oxygen processes: better describing the processing of dissolved and particulate organic matter in the water column and the associated benthic-pelagic relationships. This requires targeted process studies at a range of sites within the Harbour (farmed, fallowed and reference) and under a range of different Harbour scale levels of oxygen depletion. The development of a reliable hydrodynamic / DO model is integral in fully addressing these questions at both the local and whole of system scale

- **Can we predict the movement and dynamics of the low DO water within the Harbour? and can we predict the influence of external drivers?**
  In order to predict the potential impact or consequence of the low DO water body (bodies) within the broader Harbour, we need to better understand the movement of that water and the external drivers of change to the water body (i.e. the effect of recharge events and the influence of wind, river flow etc.). We also

need to better understand the spatial characteristics (extent and patchiness) of DO in Macquarie Harbour bottom waters.
Proposed Research
A reliable hydrodynamic / DO model is integral to understanding the drivers and dynamics of the low DO water in the Harbour and would be invaluable in helping to direct more targeted ecological and process studies.

Benthic Condition

The most recent data from the FRDC 2015-024 benthic surveys has highlighted significant deterioration in conditions under and around the farms, and provides significant concerns regarding the potential for sediment “souring”. Given the additional adverse signals observed in the benthic water column, this has serious implications for management and the extent to which sediments can sustain ongoing farming at current levels. There is a need to determine a recovery/ remediation strategy, and to establish what level of farming might be sustainable from a benthic perspective.

KEY QUESTIONS/ ISSUES:

- **Can we manage the sediments to recover?**
  When farming ceases: how long does the sediment under cages take to recover such that farming could recommence? how long does the sediment off-lease take to recover to natural background conditions (in terms of both diversity and functionality)? Once re-stocked, do sediments deteriorate more rapidly and what does that mean for management (farm and compliance)? Are there any practices that could be employed to enhance remediation?
  Proposed Research
  This needs a targeted gradient based study of sediment recovery – taking into account level of impact, different farming practices, location in the Harbour (spatial/ sediment type differences) and temporal (seasonal) differences. Sampling would be conducted in conjunction with a fallowing/ remediation strategy on and off-lease, and at sites with varying degrees of initial impact (highly, moderately and mildly impacted). Studies may also include laboratory based investigations and field trials of selected remediation options where appropriate. In addition, it is proposed that time-lapse cameras be deployed at a number of the proposed cage fallowing sites to provide a much better (fine-temporal scale) understanding of the visual transition stages and how this relates to ecological performance/ farm management.

- **How is benthic condition/ recovery influenced by bottom water condition?**
  The normal process of recovery and ecological succession associated with organic enrichment is strongly influenced by the ability of the infaunal species and the microbial communities in the sediments to access oxygen from the overlying water; this drives the processes essential for recovery (e.g. denitrification). If oxygenated water is not available these processes either cannot occur or will occur more slowly, and recovery will be affected. It is not clear to what extent the oxygen depleted bottom waters in Macquarie Harbour will affect recovery and understanding this is important for effective management.

Proposed Research
Targeted assessments (i.e. field and laboratory-based experiments) aimed at improving our understanding of how specific oxygen levels might affect field based recovery and sediment processes could be run in conjunction with recovery/ fallowing surveys proposed in the previous section and at key sites within the Harbour. In order to relate the resultant information to management these studies would need to be linked to both modelling of the low DO water body (bodies) in the Harbour and to actual measurements of bottom-water oxygen.

We need to know not only how changing farming practices can improve recovery but also whether and to what extent those practices need to be modified to different environmental conditions (i.e. the sedimentary environment and the benthic oxygen environment).

Compliance Monitoring

At present there are still concerns that the compliance monitoring is not adequately supporting management - in that the monitoring needs to be able to provide assurance that farming is sustainable both for the salmon farmers and for the broader environment. Further research is needed to validate existing monitoring strategies and if necessary to recommend additional monitoring. The research in the existing FRDC project 2015-024 and proposed above will go some way to achieving this but it is also important to include quite specific management/ compliance objectives in that research: i.e. studies that will enable a better understanding of the impact and recovery potential associated with different farm management strategies (i.e. how long do the sediments need to recover and do we need to adjust management strategies for different regions of the Harbour).

Proposed Research
In addition to the research proposed above, it is suggested that the ROV assessments currently undertaken annually be carried out quarterly and that benthic grabs be taken in association with that sampling (this could be tied in with the benthic surveys outlined above). It is also suggested that the sampling (ROV and grabs) follow the sampling approach/ design outlined in the current FRDC 2015-024 project (i.e. transect/gradient approach rather than collecting data just at compliance sites) and that the research proposed above under Benthic Condition assessment be used to inform the compliance assessments.

Finally, given that the data available to date tend to suggest that there may be a broader-scale or even “Harbour-wide” change occurring in the benthic ecology, it is proposed that the benthic surveys are expanded to include sites across the broader Harbour. This should also include sampling methodology to monitor changes in the abundance of large mobile fauna, such as crabs, which are a key component of the skate diet.

Skate Ecology

The suggestion that there is a significant and increasing area of the seabed in Macquarie Harbour where the oxygen levels are highly reduced and infauna markedly depleted has clear negative implications for the endangered Maugean skate, and there is a need to better understand the significance of this for the future viability of the skate population in Macquarie Harbour.

Proposed Research
Consequently, we recommend that the population surveys continue and that these be conducted in association with the research proposed above, so that they can be informed by, and add value to, the understanding of environmental condition associated with those research activities. Moreover, concern remains that tolerance to variable DO levels might be quite different between eggs, juveniles and adults so research to examine the physiology of eggs and adults is needed. This should include a targeted survey of egg distribution within the Harbour and laboratory trials to assess physiological responses to varying levels of DO and potentially salinity. It would also be useful to tag a number of skate using VEMCO DO tags to get a better understanding of just what DO conditions they experience in the wild.

ACKNOWLEDGEMENTS

We wish to thank all of the researchers and scientists who provided their data and insights for this review. In particular, the IMAS team: Dr Jeremy Lyle, Associate Professor Jayson Semmens, Dr Kilian Stehfest, Dr Justin Bell, Dr Neville Barrett, Mr Jason Beard, Dr Christine Crawford, Professor Chris Carter and Professor Caleb Gardner.

REFERENCES

Aquadynamic Solutions 2015. MHDOWG Update Report (Draft) April 2015. Aquadynamic Solutions Sdn Bhd.

Bell, J.D., Lyle J.M., Semmens, J.M., Awruch, C., Moreno, D., Currie, S., Morash, A., Ross, J., Barrett, N. (2016) Movement, habitat utilisation and population status of the endangered Maugean skate and implications for fishing and aquaculture operations in Macquarie Harbour. FRDC Final Report Project No. 2013/008

Crawford, C, Buxton, C and Main, A., (2013) Macroalgal monitoring in Macquarie Harbour, Tasmania. FRDC Final Report Project No. 2011/086

Cresswell, G. R., R. J. Edwards, and B. A. Barker. (1989) Macquarie Harbour, Tasmania-seasonal oceanographic surveys in 1985. Papers and Proceedings of the Royal Society of Tasmania 123:63-66.

Edgar, G. J., N. S. Barrett, and D. J. Graddon. (1999) A Classification of Tasmanian Estuaries and Assessment of Their Conservation Significance Using Ecological and Physical Attributes, Population and Land Use. Hobart, Tasmania

Koehnken, L. (1996) Macquarie Harbour - King River Study: Technical Report, Department of Environment and Land Management, Hobart.

Lucieer, V., Lawler, M., Morffew, M and Pender, A (2009) Mapping the Gaps. 195pp

Macquarie Harbour Dissolved Oxygen Working Group. Final Report October 2014.

O'Connor, N A, F Cannon, B Zampatti, P Cottingham, and M Reid. (1996) Mount Lyell Remediation: A Pilot Biological Survey of Macquarie Harbour, Western Tasmania. Barton, ACT, Australia.

Riedel et al (2014) Effect of hypoxia and anoxia on invertebrate behaviour: ecological perspectives from species to community level. Biogeosciences (11) 1491-1518

Revill, A.T., Ross, J. and Thompson, P.A. (2016) Investigating Dissolved Oxygen Drawdown in Macquarie Harbour. CSIRO, Australia. Report to Huon Aquaculture

Ross, D.J, Hartstein, N., Macleod, C.M, Auluck, M., Lucieer, V., Cook, P., Valentine, J (2015) Characterising benthic pelagic interactions in Macquarie Harbour - organic matter processing in sediments and the importance for nutrient dynamics. FRDC Final Report Project No. 2012/047

Ross, D.J, McCarthy, A., Davey, A., Pender, A., Macleod, C.M (2016) Understanding the Ecology of Dorvilleid Polychaetes in Macquarie Harbour: Response of the benthos to organic enrichment from finish aquaculture. FRDC Final Report Project No. 2014-038

Ross, D.J.; Revill, A.T.; Bodrossy, L. and Nichols, P.D. (2016) Pelagic DO Study - Particulate Organic Matter - Source, Composition and Degradation (Objective 2). Report to TSGA/MHTWG

Talman, Sonia, Nicholas O'Connor, Brenton Zampatti, and Frances Cannan. (1996) Mount Lyell Remediation: Monitoring of Benthic Invertebrates in Macquarie Harbour, Western Tasmania. Barton, ACT, Australia.

Vaquer-Sunyer & Duarte (2008) Thresholds of hypoxia for marine biodiversity PNAS (105) 15452-145457

Vaquer-Sunyer & Duarte (2010) Sulphide exposure accelerates hypoxia-driven mortality. Limnology & Oceanography 55(3) 1075-1082