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Understanding oxygen dynamics and the importance for benthic recovery in Macquarie Harbour

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Executive Summary

Background

This study, undertaken by the Institute for Marine and Antarctic Studies (IMAS) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) was commenced to investigate deteriorating benthic conditions in Macquarie Harbour; in particular the very low dissolved oxygen (DO) levels observed in the middle and bottom waters in spring 2016 (Ross & Macleod 2016a). This project was designed to provide a clearer understanding of both the effectiveness of fallowing and passive remediation for benthic recovery, and the drivers and importance of oxygen dynamics for recovery of benthic conditions in Macquarie Harbour.

Objectives

Specifically, the project objectives were to:

1. Determine the benthic response to changing environmental conditions (principally DO) and farming operations (i.e. fallowing)
2. Document spatial and temporal variability in oxygen dynamics via the observation network and modelling
3. Quantitatively describe the physical drivers of Macquarie Harbour circulation, stratification, mixing and dissolved oxygen tracer drawdown and recharge
4. Provide advice to government and industry on benthic and water column condition in the Harbour and how it relates to ongoing management actions (operational and regulatory).

Methodology

To address the above objectives, the project comprised four work packages.

Work package 1(WP1) assessed benthic recovery over time, building on the 6 previous surveys, which documented benthic conditions up until the major decline in faunal abundance and diversity observed in October 2016, with repeat surveys of all lease and external sites every 4-6 months until early 2020.

Work package 2 (WP2) saw the further development of the real time DO observation network in the harbour. This included the deployment of:

- three vertical strings of acoustic (real-time) DO sensors in the central region of the harbour,
- a profiling mooring located at the deepest part of the main basin, and
- two additional logger strings (not real-time) to extend the observation network further south (inside the WHA) and north (close to the entrance to the ocean).

Work package 3 (WP3) involved the further development by CSIRO of their Near Real Time (NRT) Hydrodynamic and Oxygen Transport model to better describe the physical drivers of Macquarie Harbour circulation, stratification, mixing and DO drawdown and recharge.

Work package 4 (WP4) involved the collection of high priority additional observations that allowed for the biogeochemical implementation of CSIRO's model to further resolve and quantify the biological and chemical contribution to oxygen dynamics in the harbour. These additional sources of data included the installation of new river and tide gauges, mapping of nutrient and DO dynamics in the harbour; targeted observations and manipulative experiments to further understand the role of microbial activity and a pilot study aimed at reconstructing the past oxygenation changes in Macquarie Harbour (MH) in the last few thousand years using the variations of redox-elements concentrations in sediment cores.

Results

A major output of this project was the provision of advice to government and industry on benthic and water column condition in the Harbour and how it relates to ongoing management actions (operational and regulatory). This took the form of eight IMAS reports released publicly through 2017-2020 on the status of dissolved oxygen and benthic conditions in the harbour based on the latest research observations. The research findings are highly cited in the EPA biomass determinations for the harbour:

https://epa.tas.gov.au/regulation/salmon-aquaculture/macquarie-harbour/management-determinations

The results provided here are based on the final IMAS report released in October 2020. We also report on the results of the paleo reconstruction of past oxygenation pilot project. CSIRO's complementary study (Wild-Allen et al, 2020) conducted as part of this project, provides the detailed results for:

- the maintenance of the CSIRO profiler and ongoing delivery of near real time and short-term forecast model results
- updates to the visualisation dashboard
- a description of the simulated harbour water quality, evaluation of oxygen and nitrogen budgets, scenario results and analysis
- analysis of observational process studies for phosphate addition and oxygen drawdown

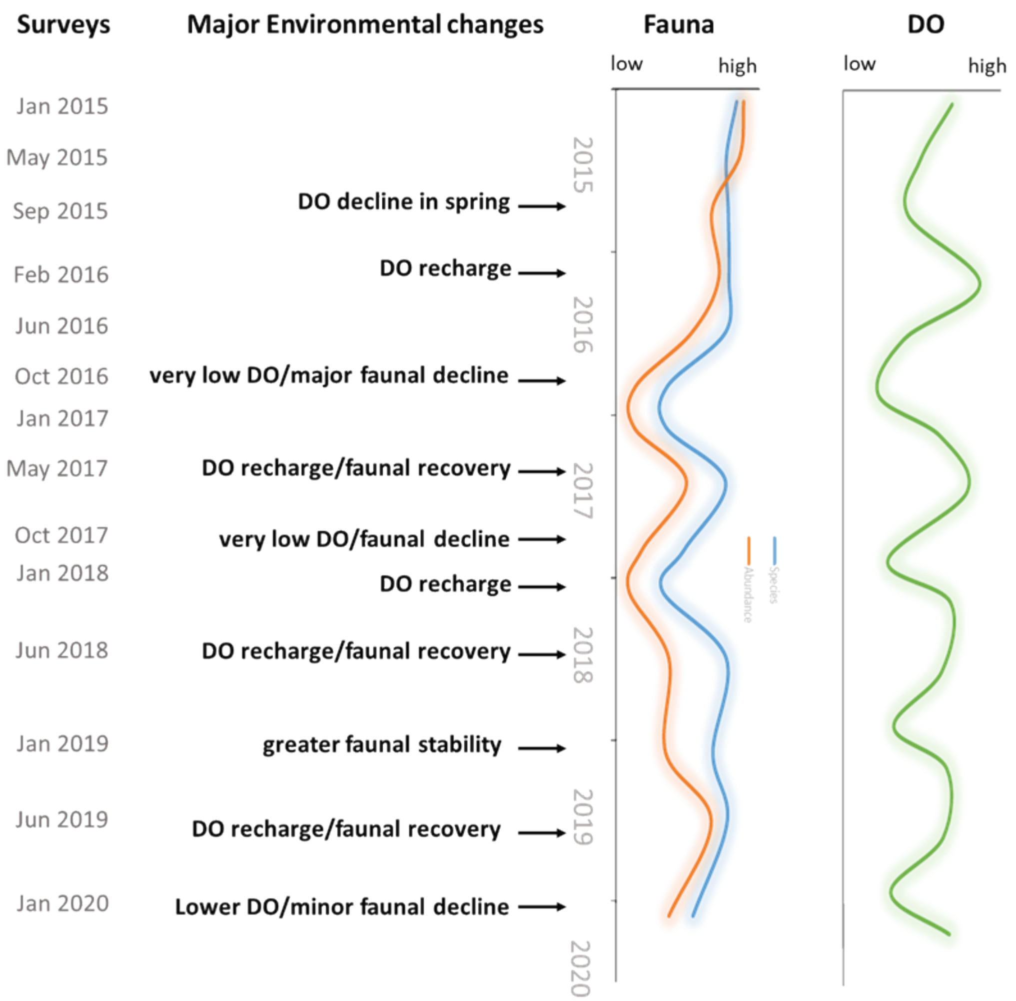
Although the results and outputs from the CSIRO report are not duplicated here, we have incorporated the recommendations in this report.

Key findings from the IMAS reports

These reports first described the deterioration of benthic and water column conditions in spring 2016, early signs of faunal recovery in the following autumn, when oxygen levels had improved, and the subsequent decline in benthic conditions when oxygen concentrations in middle and bottom waters returned to very low levels in spring 2017. Since then, oxygen concentrations in the middle and bottom waters have remained variable, declining each spring, and then increasing through summer and autumn due to oceanic and wind driven recharge. In spring 2018 oxygen levels did not decline as far, or for as long, as in the previous springs and faunal abundance and diversity was less affected as a result. Surveys in January and June 2019 documented the improved benthic conditions, highlighting that both faunal abundance and the number of species had returned to or were closely approaching the range observed prior to the decline in spring 2016-early 2017 at the majority of both lease and external sites. This final report presents the results and interpretation of a repeat survey of benthic communities in January 2020 and DO monitoring data up until March 2020.

In spring 2019 oxygen concentrations in the middle and bottom waters again declined to low levels and these conditions persisted for longer than in spring 2018. Oceanic recharge of bottom water was not observed until late December 2019 when the river flows decreased, and the halocline became shallower. Despite the extended period of low bottom water dissolved oxygen concentrations, macrofaunal abundance and diversity in January 2020 were similar to that observed in the January 2019 survey. Faunal abundance and the number of species at the external sites throughout the harbour have returned to and remain well within the range reported before the decline in spring 2016 – early 2017.

The following schematic shows the timeline of changes in benthic faunal communities and the major environmental changes observed over the course of this study.



The presence of *Beggiatoa* continues to remain low relative to that observed in spring 2016/summer 2017. *Beggiatoa* was observed on 15 of 51 lease dives in January 2020, similar to its presence in 2019 when it was observed on 12-15 of the 51 lease dives across the January, June and September ROV surveys. When present, *Beggiatoa* was most often categorised as patchy, however in the January surveys there were more observations of *Beggiatoa* as a thin mat. At the external sites, the presence of *Beggiatoa* also remained lower than observed in 2016/17; it was observed at 5 of the 28 sites in January 2020, and in all cases categorised as patchy.

The presence of dorvilleid polychaetes remained highly variable. In January 2019, their presence on farm dives had increased relative to previous surveys, but in June and September 2019 they were less abundant. In January 2020, dorvilleid abundance again increased, and this change was largely attributed to their increased presence and abundance at leases 3 and 5. At the external sites, they were also more abundant in January 2019 and 2020 compared with June and September 2019. Most observations at the external sites had lower dorvilleid scores.

Each year since the major deterioration of benthic conditions observed in spring 2016, we have observed an improvement in benthic conditions in autumn-winter and a subsequent deterioration during the following spring. This response pattern appears to be well aligned with the decline in oxygen concentrations in middle and bottom waters each spring and subsequent replenishment of oxygen due to oceanic and wind driven recharge through late spring to autumn. In 2019 we reported improved benthic conditions compared with previous years and attributed this to the less severe decline in DO in the preceding spring of 2018 relative to that observed in spring 2017 and 2016. As expected, there was a decline in macrofaunal abundance and number of species in January 2020 following the decline in DO in the preceding spring of 2019. Despite the more pronounced and prolonged decline in DO in spring 2019 compared to spring 2018, benthic conditions (including macrofaunal abundance and diversity) were similar to those observed at the same time the previous year in 2019. Although the latest results are consistent with improved benthic conditions over recent years, oxygen levels in the middle and bottom waters of the harbour remain low. The more prolonged and pronounced decline in DO in late 2019 again demonstrate the pivotal role that the weather, both directly and indirectly (e.g. wind, river flow) plays in influencing the magnitude and extent of the seasonal DO decline, and thus, the capacity for DO to reach levels that may lead to a deterioration in benthic conditions.

Recommendations

Recommendations are broken down into three key areas:

Benthic ecology

- Undertake benthic surveys as part of MHEMP monitoring program, but at a reduced frequency (i.e. every 1-2 years) and at key sites (i.e. harbour wide external site plus selected transect sites)
- Continue biannual monitoring of sediment health using ROV visual assessments
- Increased sampling/research to better understand potential effects of low DO on higher trophic levels/key taxa (e.g. Maugean skate)

Monitoring

- Consolidation and review of environmental monitoring and better integration across real time data and parallel sampling programs

Modelling

- Improved accuracy of hydrodynamic model via installation of river flow gauges in the lower reaches of the Franklin-Gordon and King-Queen River catchments and mapping of entrance bathymetry
- Improved forecasting capability of model via ensemble model forecasting (using the available range of BoM model forecasts), data assimilation of near real time data sets, a catchment model (including predicted dam releases) and an automated alert system to improve appropriate forecast delivery
- Additional model scenarios to better characterise the impact of contrasting anthropogenic loads and seasonal dam releases on water quality
- Extension of the analysis of model results (including use of remote sensing) to incorporate west coast shelf environment

Keywords

Dissolved oxygen, benthic fauna, salmonid aquaculture, Macquarie Harbour, sediment health

Introduction

In light of deteriorating benthic conditions in Macquarie Harbour, and in particular the very low dissolved oxygen (DO) levels observed in the middle and bottom waters in spring 2016, the Institute for Marine and Antarctic Studies (IMAS) prepared a report for the Environment Protection Authority (EPA) and Department of Primary Industries, Parks, Water and Environment (DPIPWE) on the science and current status of the benthic and water column environments in Macquarie Harbour (Ross & Macleod 2017a). That report summarised the environmental research and observations from Macquarie Harbour and presented the latest observations of the benthic ecology and water column conditions in the context of the collective information.

A key observation from the 2016 report was the major decline in the total abundance and number of species collected from the benthic fauna in the spring (October 2016) survey compared to previous surveys. The increase in *Beggiatoa* bacteria mats on the sediments in and around marine farming leases in the spring 2016 ROV compliance surveys provided further evidence of deteriorating sediment conditions. This deterioration in sediment conditions was shown to coincide with very low DO concentrations in bottom and mid waters of the harbour. However, the decline in benthic fauna and DO (bottom and mid water) was not uniform throughout the harbour. The lowest levels of DO and the greatest changes in fauna occurred at sites in the mid- and southern end of the harbour, with the sites closer to the harbour entrance and the ocean appearing to be less affected; this pattern was observed at both lease and external (harbour-wide) sites.

This review formed part of the information used by the EPA to support their decision to enforce reductions in the harbour wide biomass limit and fallowing of multiple cage sites across the harbour. Key challenges facing farmers and regulators are understanding the capacity of Macquarie Harbour to support finfish aquaculture and predicting the length of fallowing required for benthic recovery. It is clear that DO concentrations have been, and will be, a major determinant of the benthic response and this has major implications for future stocking plans in the harbour. As such, there is a clear need to better understand the drivers of oxygen dynamics, the influence of DO concentrations on benthic conditions and the effectiveness and duration of fallowing and remediation strategies. With a strong commitment from both industry and government, the project FRDC 2016-067: *Understanding oxygen dynamics and the importance for benthic recovery in Macquarie Harbour* was funded to provided information that is essential for both operational management of farming activities and the sustainable management of aquaculture in Macquarie Harbour over the longer term.

This report provides an update on environmental conditions in Macquarie Harbour based on the most recent benthic surveys conducted in January 2020 and water column observations up until March 2020.

Objectives

The project objectives were to:

1. Determine the benthic response to changing environmental conditions (principally DO) and farming operations (i.e. fallowing)
2. Document spatial and temporal variability in oxygen dynamics via the observation network and modelling
3. Quantitatively describe the physical drivers of Macquarie Harbour circulation, stratification, mixing and dissolved oxygen tracer drawdown and recharge
4. Provide advice to government and industry on benthic and water column condition in the Harbour and how it relates to ongoing management actions (operational and regulatory).

Method

The project was conducted as four work packages (WP), specifically:

Work Package 1: Assessment of benthic recovery over time.

WP1 assessed benthic recovery over time, building on the 6 previous surveys, which documented benthic conditions up until the major decline in faunal abundance and diversity observed in October 2016, with repeat surveys of all lease and external sites every 4 months[1].

In January 2020, IMAS conducted a benthic survey of five leases and 24 sites external to leases within Macquarie Harbour (Figure 7, Table 1). This represents the 14th benthic survey conducted since the beginning of 2015 under consecutive FRDC projects (FRDC 2014-038, FRDC 2015-024, FRDC 2016-067). The work was initiated (via. FRDC 2014-038) when video footage identified an increase in abundance of dorvilleid polychaetes. It was also noted that there were two dorvilleid species clearly visible in the video footage. Given that these species were used as indicators of enrichment it was felt that it was important to understand the distinction between these two species, and whether their environmental responses were comparable. FRDC 2014-038 identified four sites (leases) for assessment in January 2015. FRDC 2015-024 was commissioned to review the effectiveness of current monitoring protocols in new farming areas (i.e. Macquarie Harbour and Storm Bay in Southern Tasmania), and undertook a broader suite of sampling at the same sites (leases) employed in project 2014-038 with sampling undertaken from May 2015 to October 2016. This final survey component of FRDC 2015-024 conducted in October 2016 (i.e. spring) revealed a major decline in the abundance and number of species of benthic fauna. Given the importance of these past observations it was felt that the research at these sites should be extended to assess benthic recovery and the effectiveness of fallowing in the harbour, and as such this current project (FRDC 2016-067) was initiated that included extending benthic sampling to an additional lease (lease 5) and adding more external sites[2] with sampling conducted from January 2017 to January 2020 (Figure 7).

[1] In the 2 year extension the benthic surveys will be conducted twice a year
[2] All external sites are at least 1km from active leases and allow comparison of benthic changes in the harbour as a whole alongside changes associated with farming and provide a means to assess temporal changes in benthic ecology.

Table 1 Benthic survey details

Survey	Survey period	Reference in report	Study
1	6/1/2015 - 30/01/2015	January 2015	FRDC 2014-038
2	25/5/2016 - 4/06/2016	May 2015	FRDC 2015-024
3	8/9/15 - 18/9/2015	September 2015	FRDC 2015-024
4	9/2/2016 - 18-2-2016	February 2016	FRDC 2015-024
5	31/5/2016 - 21/06/2016	June 2016	FRDC 2015-024
6	11/10/2016 - 3/11/2016	October 2016	FRDC 2015-024
7	17/1/2017 - 16/2/2017	January 2017	FRDC 2016-067
8	16/5/2017 - 7/6/2017	May 2017	FRDC 2016-067
9	10/10/2017-25/10/2017	October 2017	FRDC 2016-067
10	16/01/2018-25/01/2018	January 2018	FRDC 2016-067
11	5/06/2018 - 20/06/2018	June 2018	FRDC 2016-067
12	15/01/2019 – 30/01/2019	January 2019	FRDC 2016-067
13	12/06/2019 – 26/06/2019	June 2019	FRDC 2016-067
14	21/01/2020 – 6/2/2020	January 2020	FRDC 2016-067

Work Package 2: Further development of the real time DO observation network in Macquarie Harbour

WP2 further developed the real time DO observation network in Macquarie Harbour, including deployment of:

i. three vertical strings of acoustic (real-time) DO sensors in the central region of the harbour,
ii. a profiling mooring located at the deepest part of the main basin, and
iii. two additional logger strings (not real-time) to extend the observation network further south (inside the World Heritage Area) and north (close to the entrance to the ocean).

Work Package 3: Further development of the CSIRO Near Real Time (NRT) Hydrodynamic and Oxygen Transport model to better describe the physical drivers of Macquarie Harbour circulation, stratification, mixing and DO drawdown and recharge.

WP3 involved the further development of the CSIRO NRT Hydrodynamic and Oxygen Transport model to better describe the physical drivers of Macquarie Harbour circulation, stratification, mixing and DO drawdown and recharge.

WP3 is fully reported in Appendix 2: Macquarie Harbour Oxygen Process model (FRDC 2016-067) CSIRO Final Report

Work Package 4: Collection of high priority additional observations to further resolve and quantify the biological and chemical contribution to oxygen dynamics using the CSIRO model.

WP4 include the installation of a new tide gauge at Strahan and mapping of nutrient and microbial dynamics in the harbour to provide information for the implementation of CSIRO's biogeochemical model to further resolve and quantify the biological and chemical contribution to oxygen dynamics in the harbour. These components are detailed in the CSIRO final report for FRDC project 2016-067: Macquarie Harbour Oxygen Process model (Wild-Allen et al, 2020).

To help put recent changes in oxygenation in the context of oxygenation/deoxygenation events over a much longer, geological period, the work package also included a pilot study using variations of redox-elements concentrations in sediment cores that were collected from Macquarie Harbour and stored at Geoscience Australia. The results of the pilot study are described in Appendix 2: Macquarie Harbour oxygenation: a paleo-perspective

Results and Discussion

A major output of this project was the provision of advice to government and industry on benthic and water column condition in the Harbour and how it relates to ongoing management actions (operational and regulatory). This took the form of eight IMAS reports released publicly through 2017-2020 on the status of dissolved oxygen and benthic conditions in the harbour based on the latest research observations.

In Ross & Macleod (2017a) we provided an overview of DO observations in the harbour since the early 1990s and outlined the steady decline observed in bottom and mid-waters since 2009 (Figure 1). In spring 2016 DO concentrations were extremely low throughout the harbour, in fact, the lowest on record. Whilst a range of independent data sets confirmed this observation, the Sense-T environmental strings provided the most detail on the evolution of these DO levels through the centre of the harbour. These strings provided real time data on DO and temperature changes throughout the water column at three farm sites along the centre of the harbour; Table Head Central closest to the influence of the ocean, Franklin near the boundary of the World Heritage Area (WHA), and Strahan, a site midway between the two (Figure 2). These three strings were refurbished and updated with the latest technology in early June 2017 and the observation network extended further south and north, with additional delayed mode data loggers deployed on a string inside the WHA to the south and on a string in the King River Basin in the north (see Figure 2). These additional strings provide important insight into the influence of boundary conditions (e.g. Gordon River and the ocean).

The contour plots produced from the three real time strings have been updated to include data up until mid-March 2020 (Figure 3-5). These figures demonstrate the cycle of recharge and replenishment of oxygen in the bottom waters through summer and autumn and the subsequent decline in winter and spring. Following the sustained period of recharge that extended from October 2018 through to May 2019, bottom water oxygen levels declined to the very low levels reported previously through spring and early summer (Figure 3-5), coinciding with a period of higher river flows and limited oceanic recharge. Data from the CSIRO mooring (Figure 6) highlight the deeper halocline through mid - winter 2019 to the end of the year. Oceanic recharge of bottom water was not observed until late December when the river flows decreased, and the halocline became shallower; this was most evident from the CSIRO profile mooring (Figure 6). Compared to the previous year, oxygen levels were lower, and the low levels persisted for longer in the spring – early summer of 2019. This is reflected in the timing of bottom water recharge of oxygen not commencing until the end of December 2019 compared with October 2018 (Figure 6).

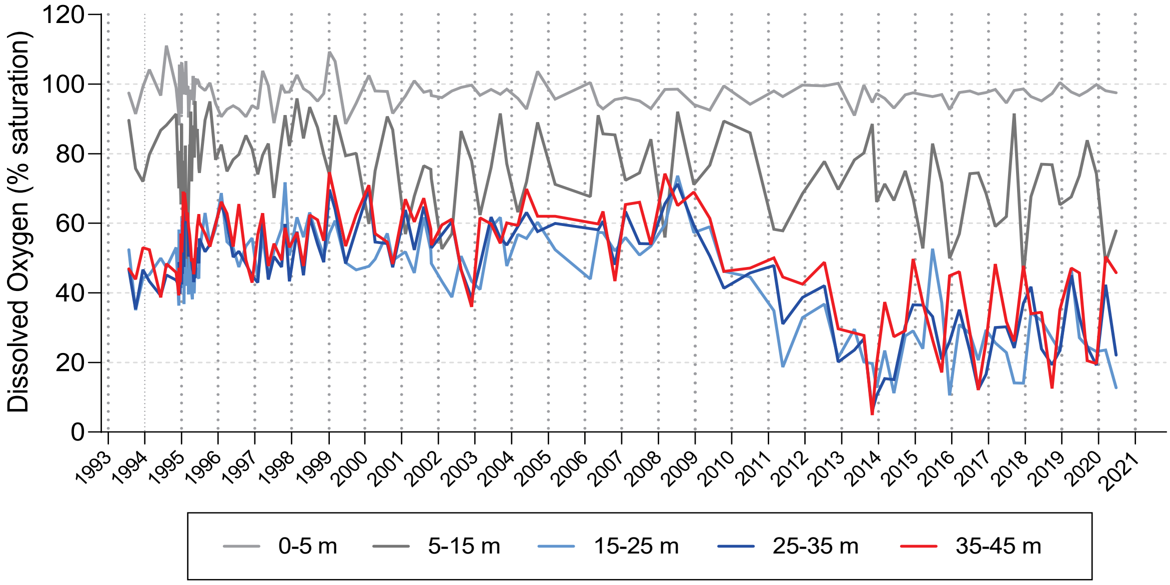


Figure 1 Long term trend in DO within a number of depth ranges at EPA site 12 (updated from MHDOWG 2014).

Figure 2 Map of Macquarie Harbour showing location of the environmental strings. The yellow sites provide data in near real time and the red sites use delayed mode data loggers. The CSIRO profiling mooring was directly adjacent to the Strahan environmental string until mid-2018 before it was moved to near the King River Basin site to help better capture the intrusion of oceanic water into the harbour.

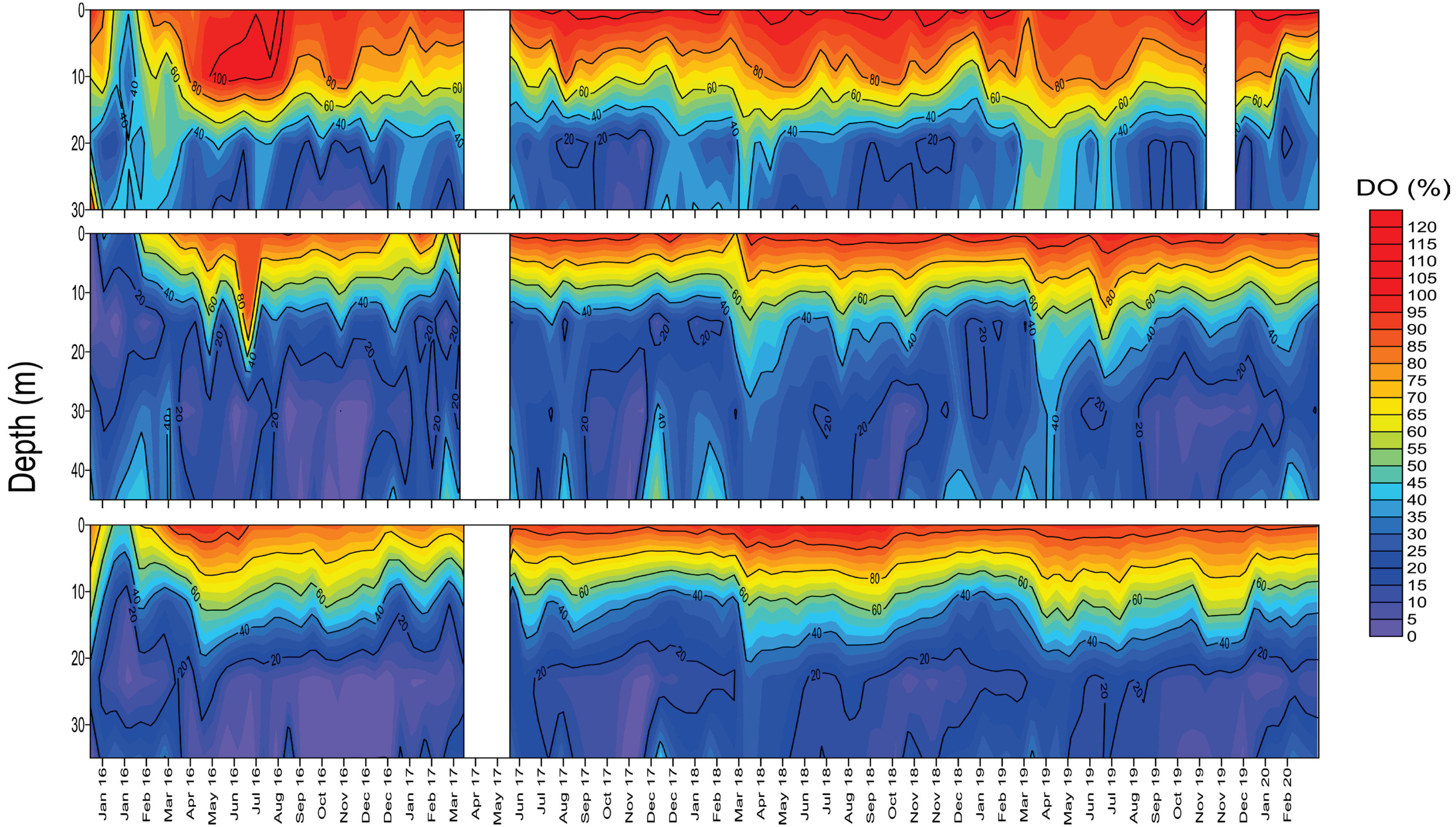


Figure 3 Contour plots showing DO profiles through the water column from the environmental strings at Table Head Central (top panel), Strahan (middle panel) and Franklin (bottom panel) over the period from December 2015 to mid-March 2020. Note, the data that underpins these plots for the period Dec 2015 to April 2017 is from the environmental sensors deployed under the Sense-T project. The sensors and associated infrastructure were replaced and updated in June 2017 as part FRDC project (FRDC 2016-067).

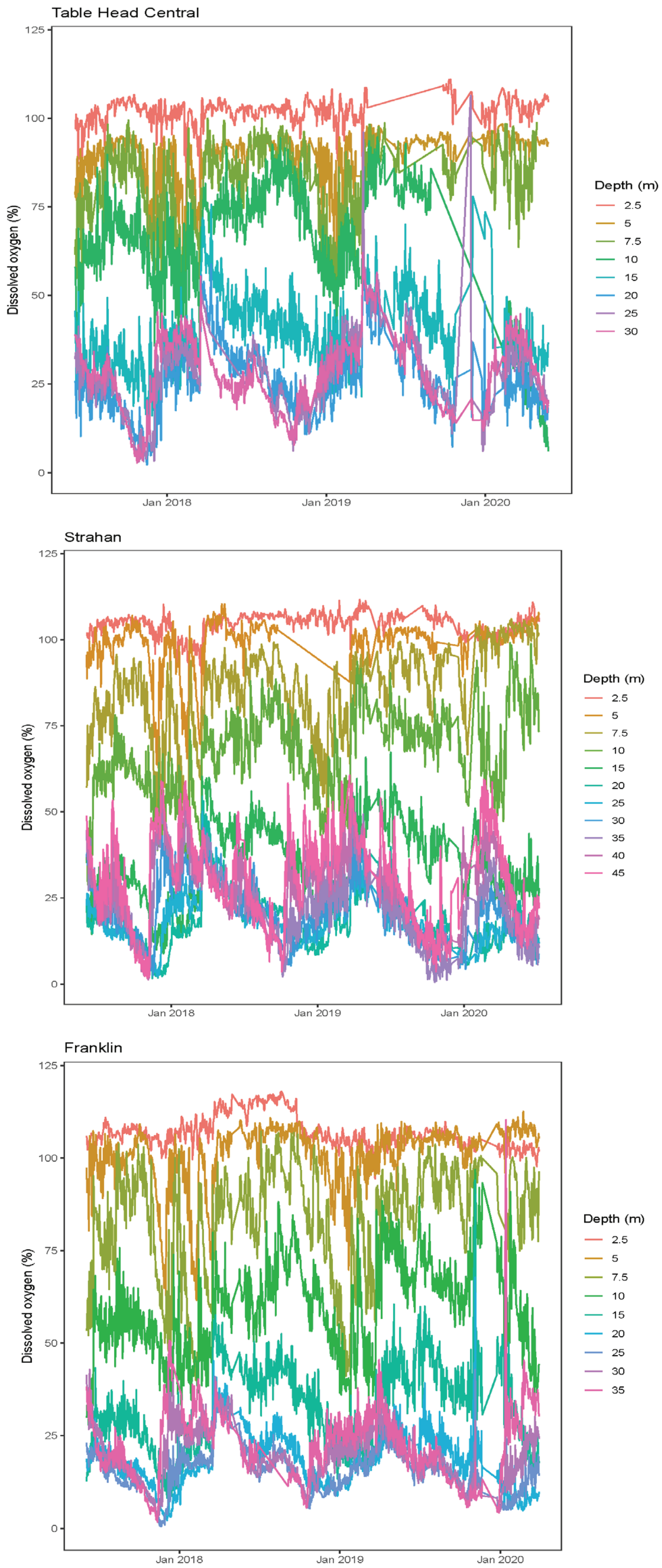


Figure 4 Daily mean DO (% saturation) levels at sensor depths from strings at Table Head Central, Strahan and Franklin over the period from the beginning of June 2017 to March 2020.

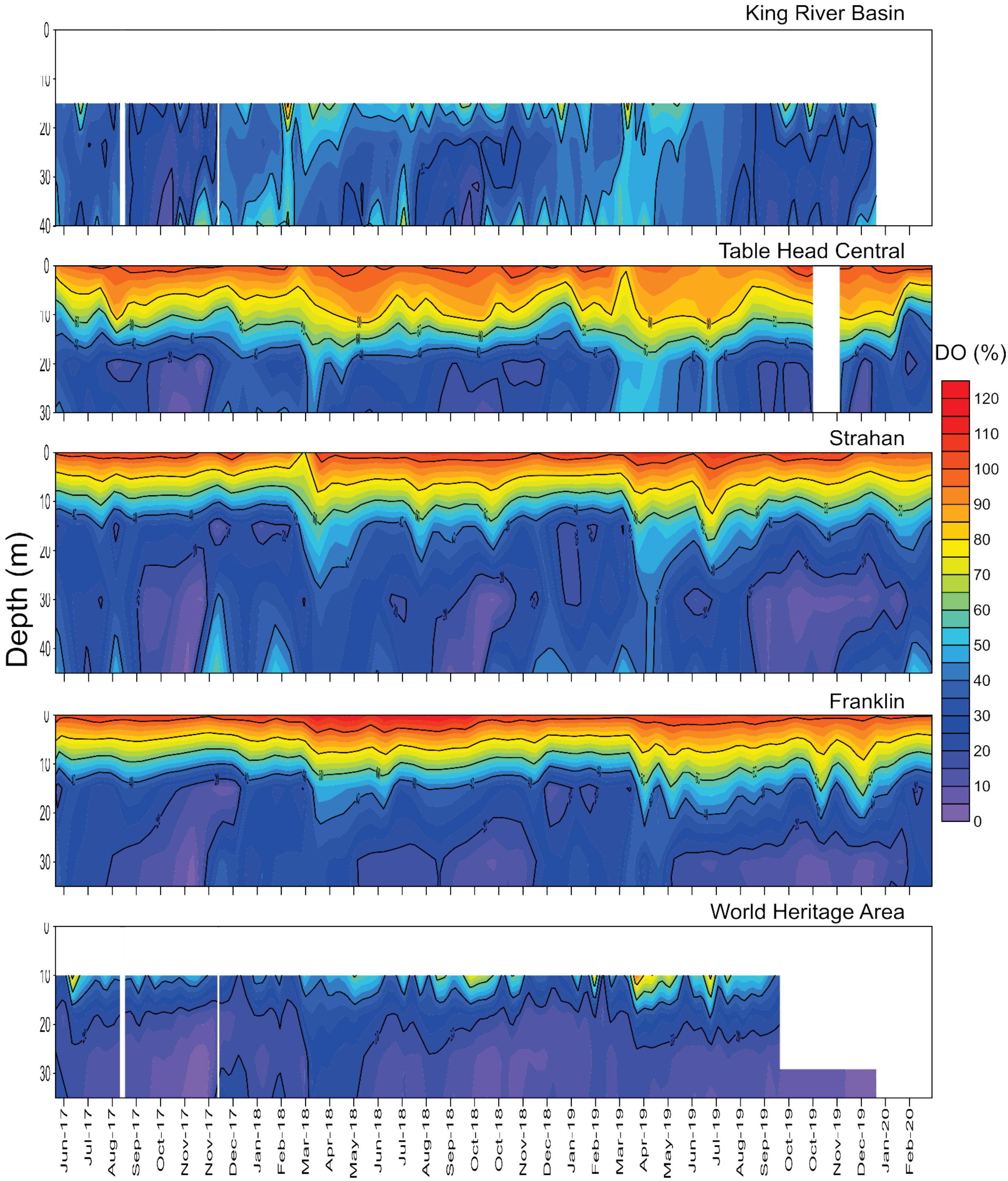


Figure 5 Contour plots showing DO profiles through the water column from the environmental strings at King River Basin, Table Head Central, Strahan, Franklin and the World Heritage Area over the period from the beginning of June 2017 to January 2020 (delayed logger strings) and March 2020 (near real time strings). This represents the data from the upgrade to the three near real time strings and the two additional strings deployed as of part FRDC project (FRDC 2016-067). Note, the two additional strings don't measure to the surface because they are in high traffic waters. Data from the 10, 20 and 25m loggers on the World Heritage Area string could not be downloaded from Sep 2019-Jan 2020 and the loggers have been sent to the manufacturer to retrieve the data.

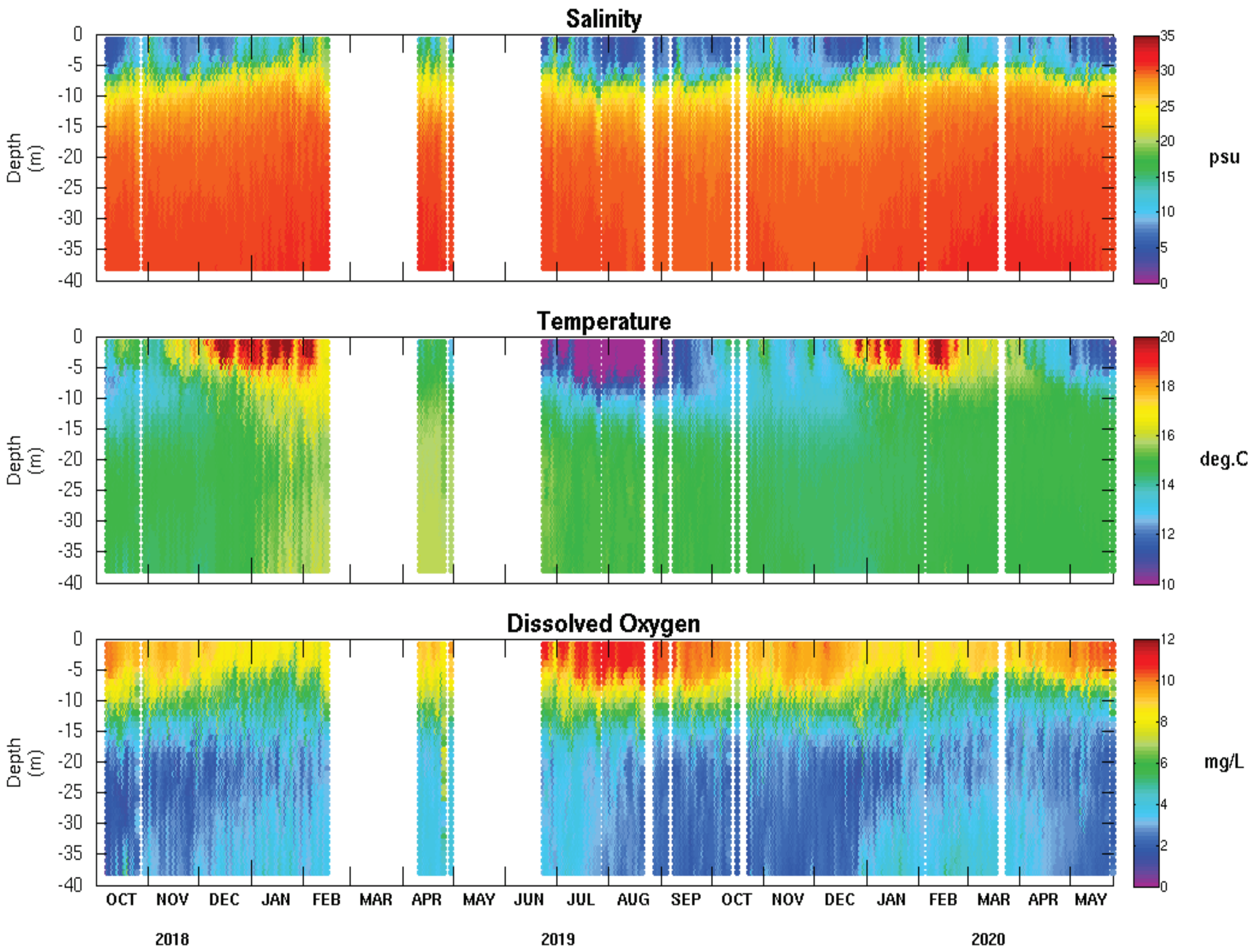


Figure 6 Observations from the CSIRO profile mooring at King River Basin site (Figure 2) showing the temporal change of water column salinity, temperature and dissolved oxygen concentration from October 2018 to May 2020. Profiling operations were suspended (i.e. the gaps in the figure) during very rough weather to avoid entanglement, and on a few occasions to enable platform maintenance.

Following the major decline in fauna observed in spring (October) 2016, we observed signs of benthic faunal recovery in both abundance and number of species in autumn (May) 2017. In spring (October) 2017 there a subsequent decline in both the abundance and number of species of benthic fauna at lease sites was observed concomitant with the return of very low DO concentrations in bottom waters throughout the harbour. In the winter (June) 2018 survey we again observed a recovery in both abundance and number of species collected from the benthic fauna relative to the decline observed in spring (October) 2017. The subsequent decline in oxygen levels in spring 2018 wasn't as low as observed in the previous two springs and didn't continue for as long. The results of the summer (January) 2019 survey of benthic fauna suggested that the fauna was less affected as a result. In the winter (June) 2019 survey, abundance and species diversity had increased from that observed in summer (January) 2019 consistent with the recovery observed in winter in previous years; however, the results varied by location. The prolonged decrease in oxygen over winter/spring 2019 resulted in fewer macrofauna and less species than in the June 2019. However, faunal abundance and species numbers were similar to that observed in January 2019 survey, although again this varied by location.

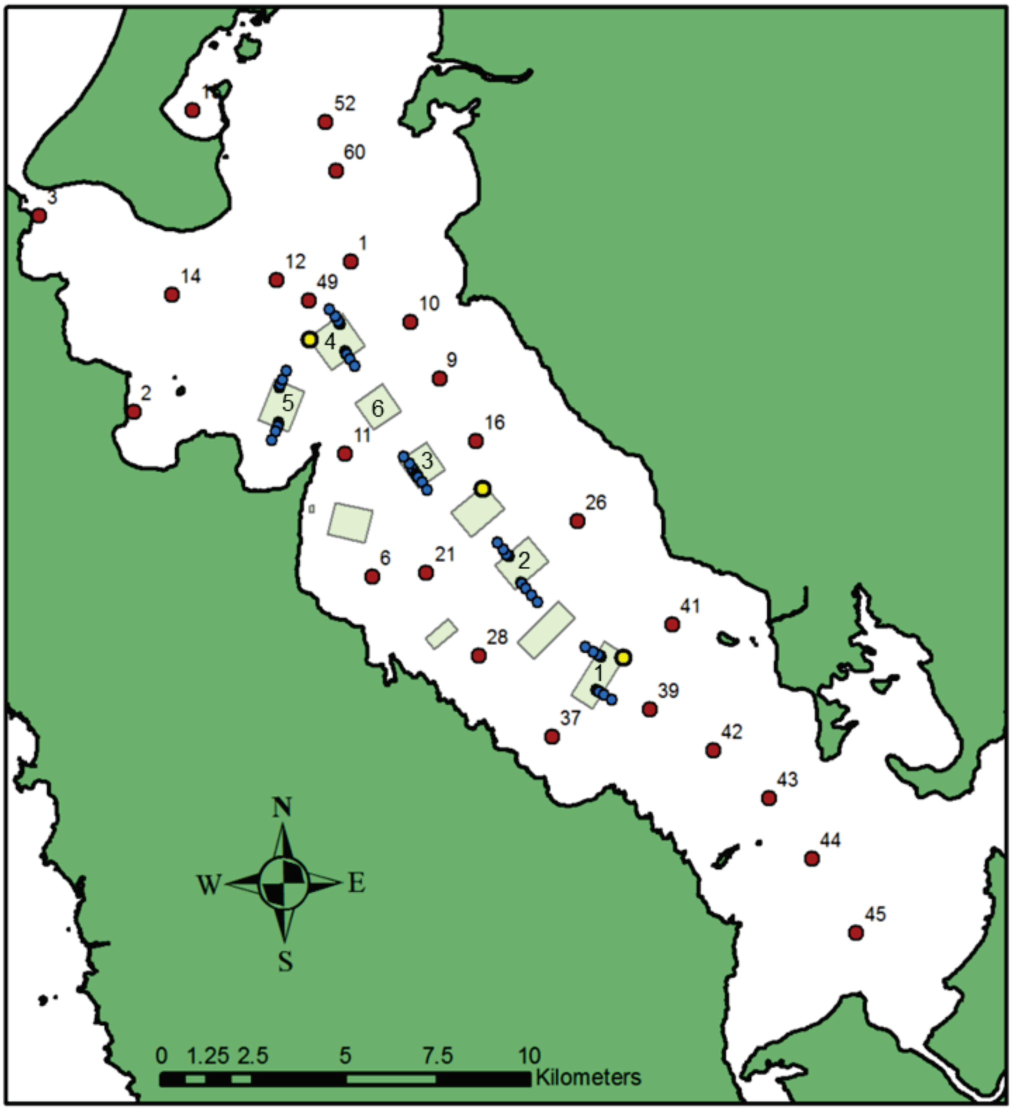


Figure 7 Maps showing external (red), lease (blue) and environmental string (yellow) sites. There are 2 transects from each of the study leases with five sites (at 0, 50, 100, 250 and 500m) on each transect.

At lease 4, the northern most of the study leases, total abundance was lower at the 0-100m sites, but similar at 250-500m, in January 2020 compared to the June 2019 survey (Figure 8). The number of species recorded was also slightly lower in January 2020, and this was mostly evident at the 50 and 100m sites (Figure 8). Although abundance and to a much lesser extent, the number of species are in the lower range reported historically at the lease, it is important to keep in mind that feed inputs, and thereby food availability to the sediments has also decreased over the same period. Bottom water DO concentrations were greater than those reported in both the January and June 2019 surveys at all distances and were at the upper range reported historically at this time of the year (Figure 8).

At lease 3, total abundance was lower at the 0 and 50m sites, but higher at 100m, in January 2020 compared to the June 2019 survey. The number of species recorded was lower in January 2020 compared to June 2019, and this was more evident at the sites closest to the cage (i.e. 0 & 50m; Figure 9). Abundances and number of species are in the lower range reported historically at the lease but are greater than the original decline in spring 2016-early 2017. At the more distant sites, abundance and to a lesser extent the number of species, remains low relative to that observed prior to the original decline (Figure 9). Bottom water DO concentrations were slightly lower in comparison to recent surveys and most previous surveys for this time of the year (Figure 9).

At lease 2, total abundance was lower at the 0 and 500m sites, but higher at the 50m sites, in January 2020 compared to the June 2019 survey (Figure 10). The number of species recorded was lower in January 2020 compared to June 2019, and this was more evident at the cage site (Figure 10). Importantly, both abundance and the number of species are within the range reported historically at the lease, including prior to the original decline from spring 2016-early 2017. Bottom water DO concentrations were within the range reported for this time of year in previous surveys (Figure 10).

At lease 1, the most southern lease, abundances were lower at all distances in comparison to the June 2019 survey, but were similar to those recorded in the January 2019 survey. The decline in abundances is likely a result of the prolonged low DO concentrations that extended until the end of December 2019 (Figure 3-5). The number of species was lower at most distances relative to the two previous surveys. Importantly though, both faunal abundances and species numbers remain higher than recorded in spring and summer of 2016/2017 and 2017/2018 (Figure 11). Species numbers and abundance have now returned to (or are approaching) the range observed prior to the decline (Figure 11). It is important to keep in mind that feed inputs, and thereby food availability to the sediments would also have decreased over the same period, and as such, we wouldn't expect faunal abundances to return to the levels seen in the first 4 or 5 surveys when feed inputs were much greater. This highlights the complex interplay between the direct effects of farm enrichment on food availability and sediment condition and the influence of bottom water dissolved oxygen concentrations.

At lease 5, abundances at most distances, on both transects were similar to or higher a in January 2020 compared to June 2019 (Figure 12). Except for at 0m on the NW transect, where species numbers were relatively similar in both the January 2020 and June 2019 surveys. Bottom water oxygen concentrations on both transects were lower than recorded in the previous two surveys, but within the range reported previously from this lease (Figure 12).

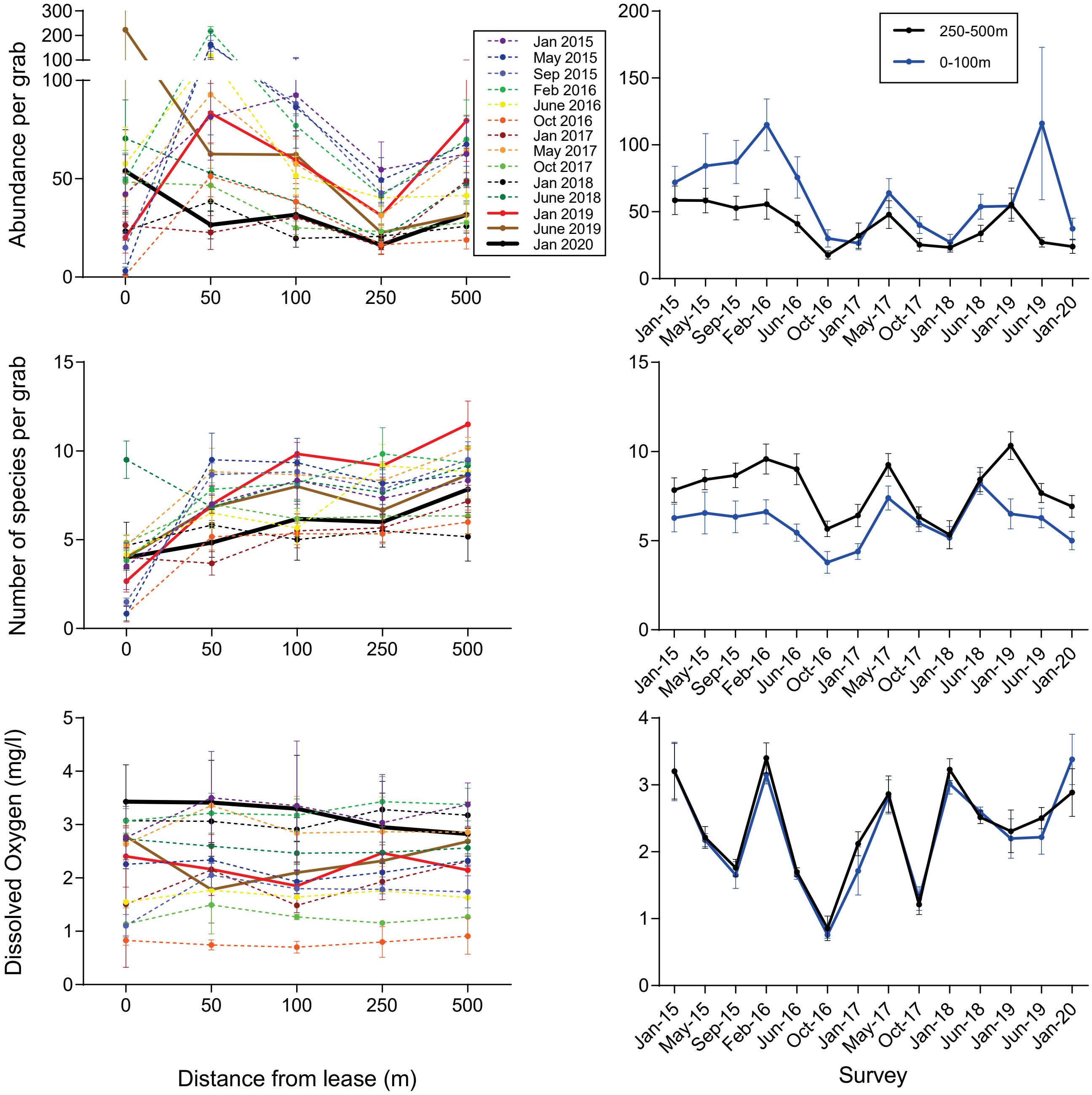


Figure 8 Lease 4 plots of total infaunal (>1mm) abundance (per grab = ~ 0.0675m²; top panel), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (bottom panel) in relation to 1 (left panels): distance from the cage (0, 50, 100, 250 and 500m from cages) for each survey, and 2 (right panels) survey date with data pooled into 2 distance categories (i.e. those closest: 0, 50 and 100m sites pooled and more distant: 250 and 500m sites pooled). In the left hand panels the data represents the mean (±SE) from two transects that radiate out from cages on opposite sides of the lease, and in the right hand panels the data represents the mean (±SE) from the two transects for each distance category. In the left hand panels the last survey (January 2020) has been highlighted with a thick solid black line.

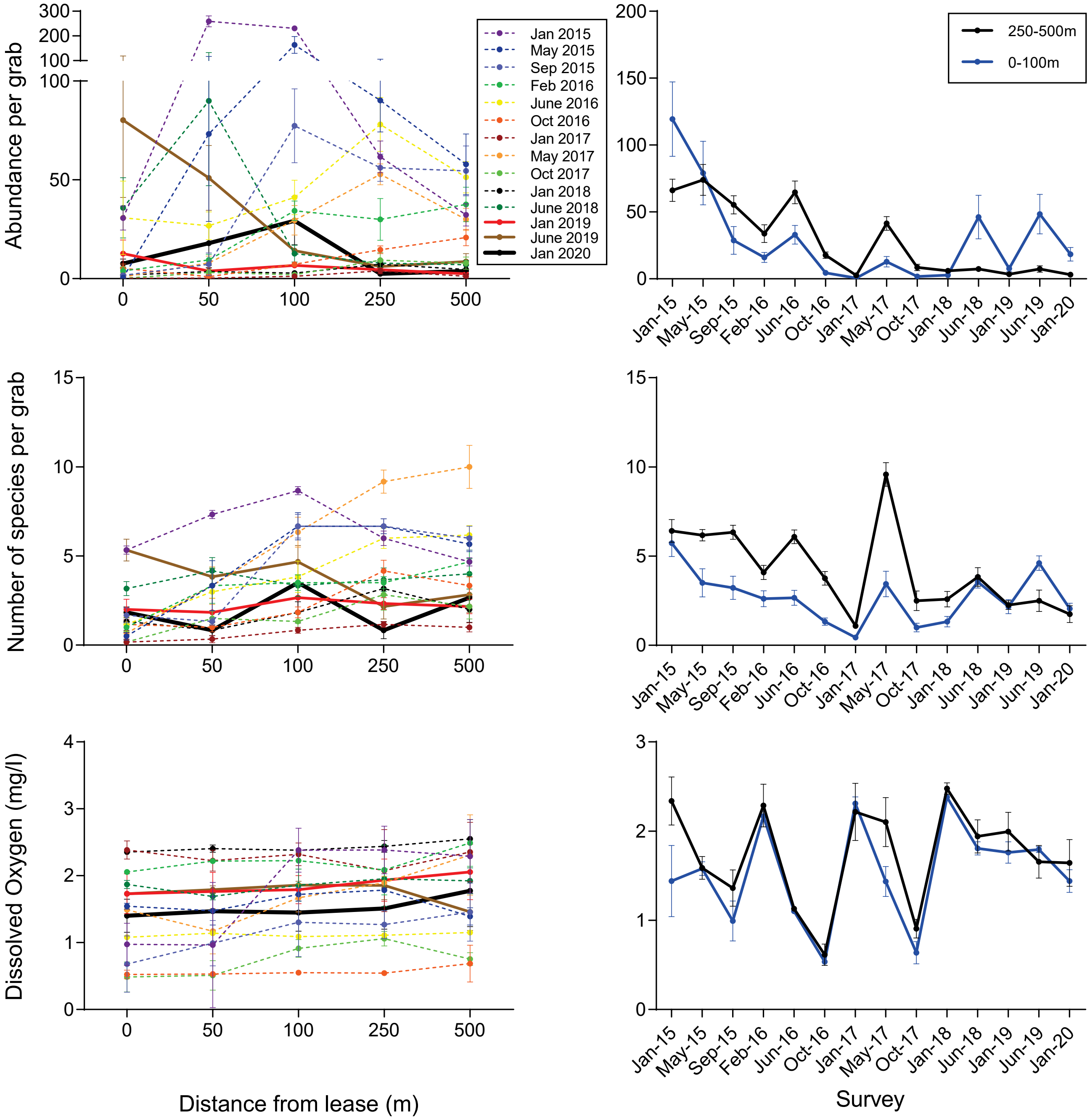


Figure 9 Lease 3 plots of total infaunal (>1mm) abundance (per grab = ~ 0.0675m²; top panel), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (bottom panel) in relation to 1 (left panels): distance from the cage (0, 50, 100, 250 and 500m from cages) for each survey, and 2 (right panels) survey date with data pooled into 2 distance categories (i.e. those closest: 0, 50 and 100m sites pooled and more distant: 250 and 500m sites pooled). In the left hand panels the data represents the mean (±SE) from two transects that radiate out from cages on opposite sides of the lease, and in the right hand panels the data represents the mean (±SE) from the two transects for each distance category. In the left hand panels the last survey (January 2020) has been highlighted with a thick solid black line.

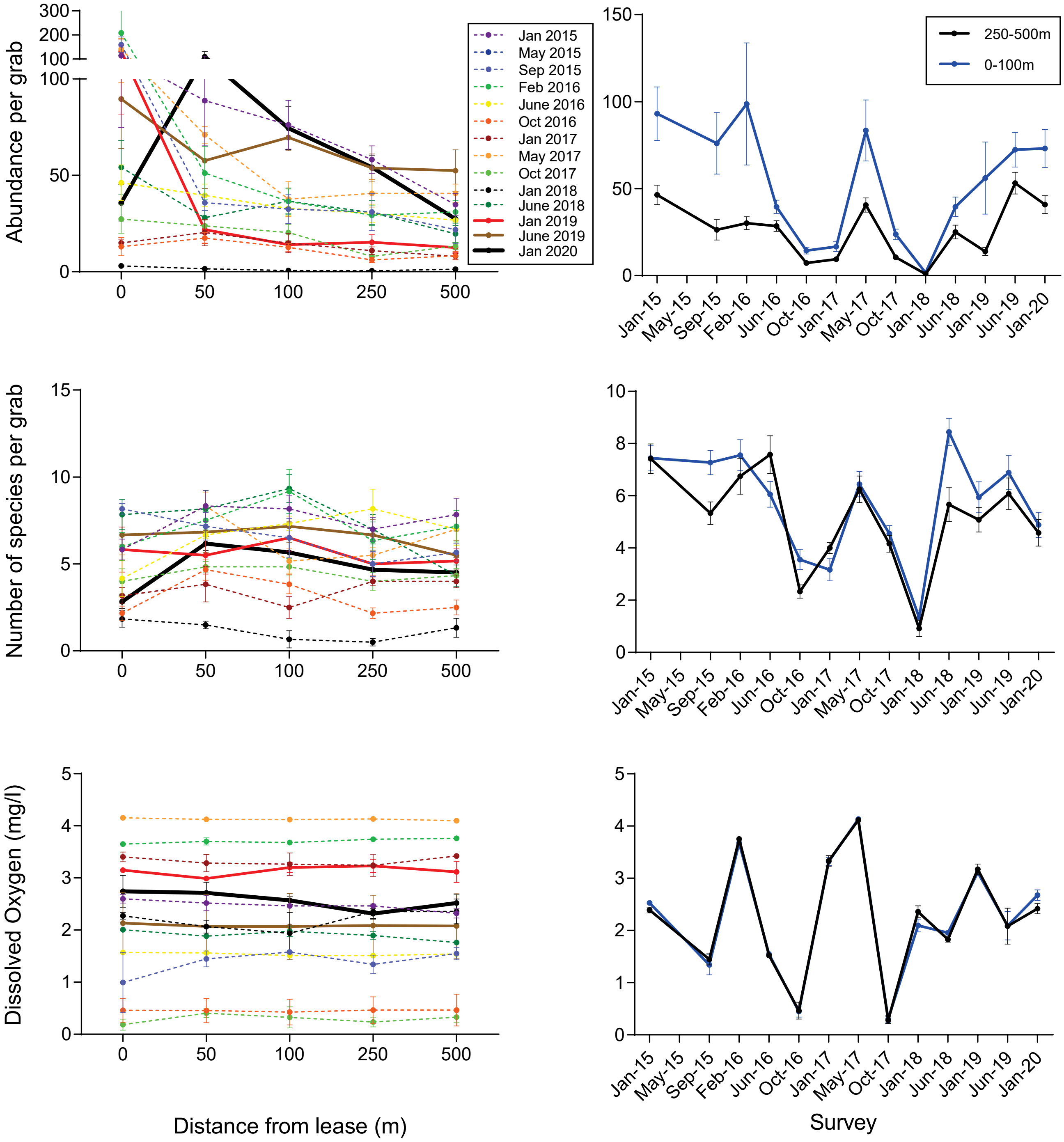


Figure 10 Lease 2 plots of total infaunal (>1mm) abundance (per grab = ~ 0.0675m²; top panel), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (bottom panel) in relation to 1 (left panels): distance from the cage (0, 50, 100, 250 and 500m from cages) for each survey, and 2 (right panels) survey date with data pooled into 2 distance categories (i.e. those closest: 0, 50 and 100m sites pooled and more distant: 250 and 500m sites pooled). In the left hand panels the data represents the mean (±SE) from two transects that radiate out from cages on opposite sides of the lease, and in the right hand panels the data represents the mean (±SE) from the two transects for each distance category. In the left hand panels the last survey (January 2020) has been highlighted with a thick solid black line. Note, lease 2 was not surveyed in May 2015.

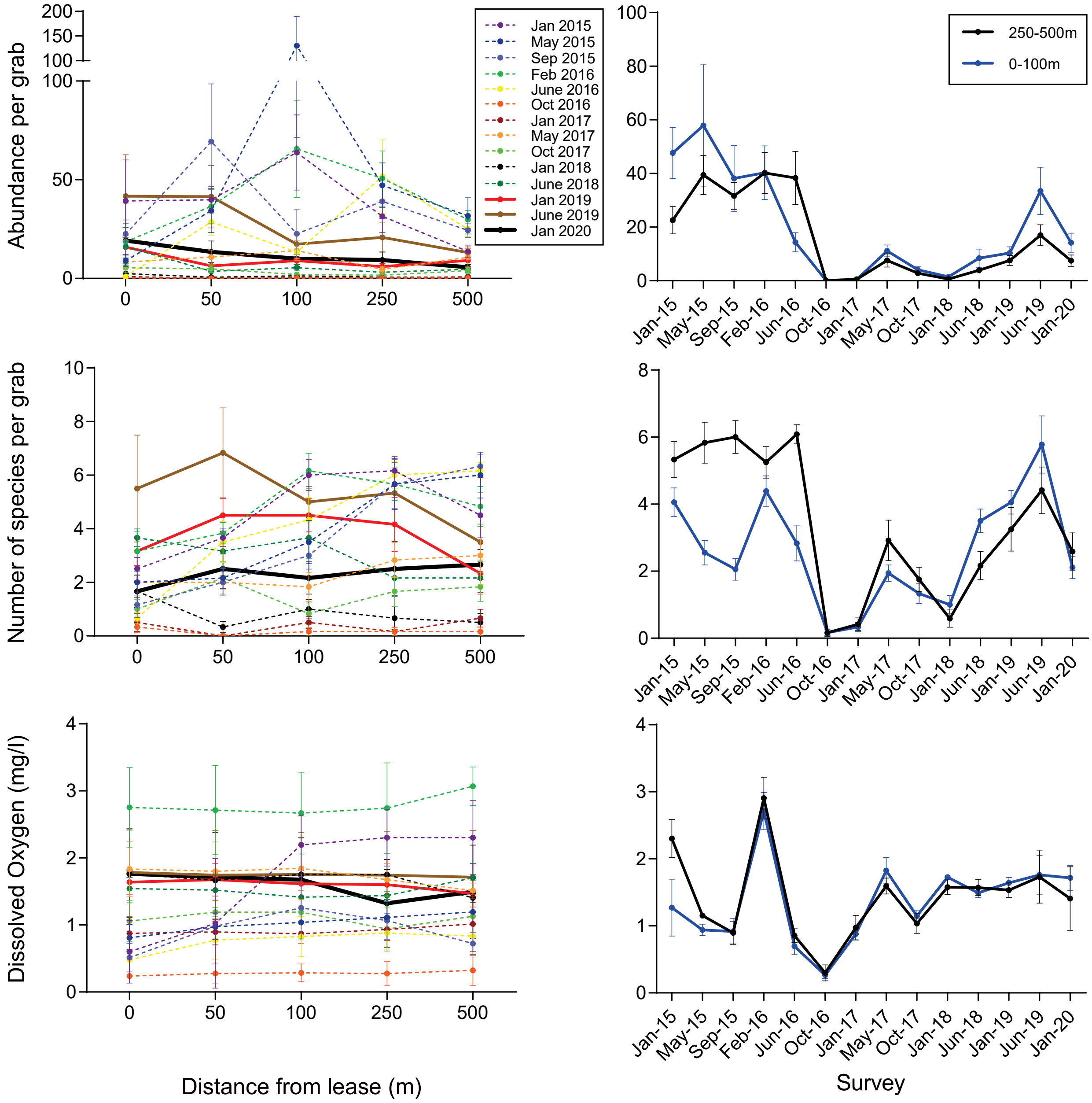


Figure 11 Lease 1 plots of total infaunal (>1mm) abundance (per grab = ~ 0.0675m^2; top panel), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (bottom panel) in relation to 1 (left panels): distance from the cage (0, 50, 100, 250 and 500m from cages) for each survey, and 2 (right panels) survey date with data pooled into 2 distance categories (i.e. those closest: 0, 50 and 100m sites pooled and more distant: 250 and 500m sites pooled). In the left hand panels the data represents the mean (±SE) from two transects that radiate out from cages on opposite sides of the lease, and in the right hand panels the data represents the mean (±SE) from the two transects for each distance category. In the left hand panels the last survey (January 2020) has been highlighted with a thick solid black line.

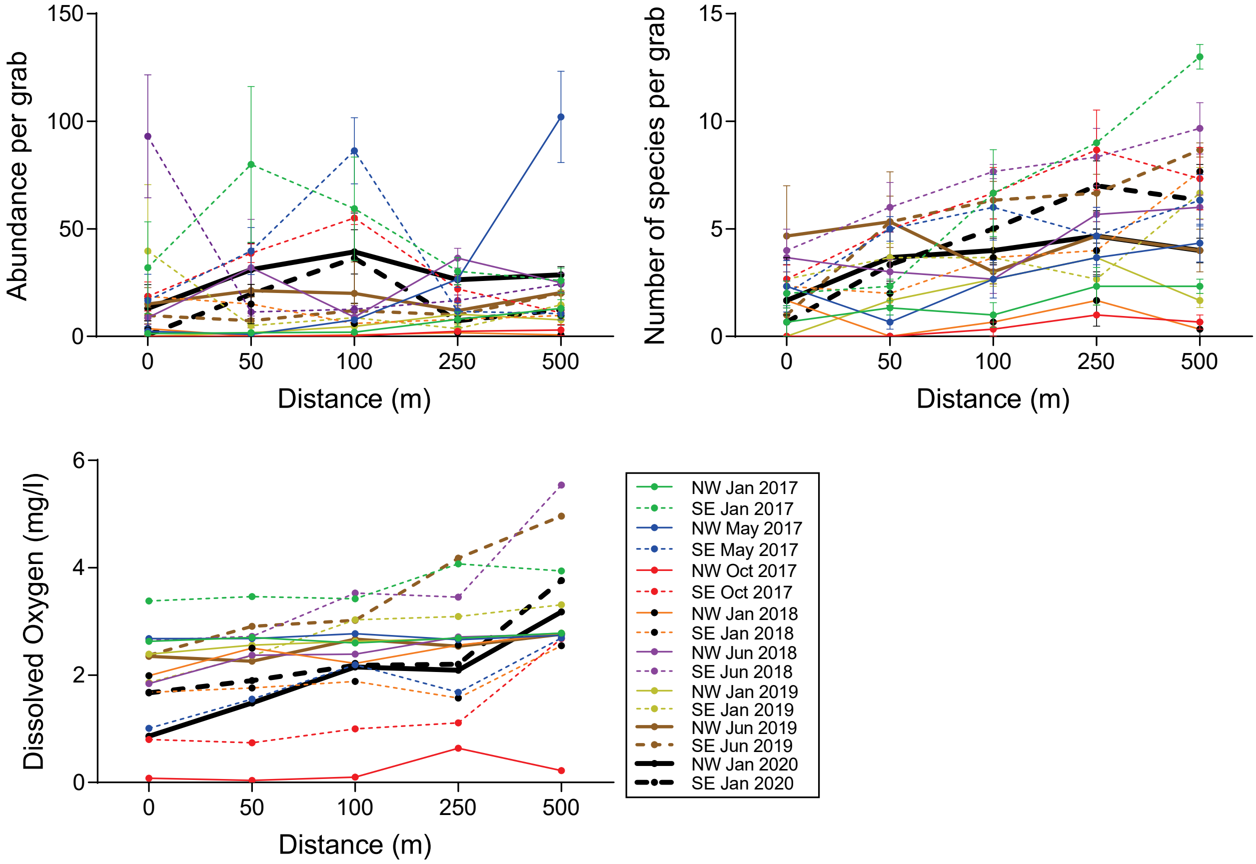


Figure 12 Plots of total infaunal (>1mm) abundance (per grab = ~ 0.0675m²), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (at 0, 50, 100, 250 and 500m from cages at lease 5 during the January 2017 – January 2020 surveys. The data shows the mean (± SE) for the North-western (solid) and South-eastern (dashed) transects.

Harbour Wide Change

Since January 2015 we have included several additional "external" sites outside the farm leases to better assess the potential for harbour wide changes. These sites are at least 1km from the nearest lease and cover similar depth ranges and habitats. These sites allow comparison of benthic changes in the harbour alongside changes associated with farming and provide a means to assess temporal changes in benthic ecology more broadly. The results suggest that the greatest changes in faunal abundance and number of species at these external (harbour scale) sites occurred from the middle to southern end of the harbour (Figure 13). The inclusion of an additional 16 external sites since January 2017 (that overlap with the harbour wide surveys conducted at the start of 2015 and 2016) further revealed that the greatest decline in abundance and number of species in October 2016 was in the deeper central region of the harbour (Figure 14).

In the June 2019 survey, faunal abundance and species numbers at the majority of the external sites were within the range recorded from our surveys prior to the decline in spring 2016 – early 2017 (Figure 14). At the four southernmost external sites (39, 42, 43 and 44), where abundances have been the slowest to recover from that original decline in spring 2016 – early 2017, faunal abundances and the number of species had returned to well within the range reported prior to the decline. In the latest survey (Jan 2020) both abundances and the number of species remained high at the southern sites. Abundance and the number of species had increased at some of the mid-harbour sites and decreased at others, but overall, the patterns remained similar and within the range recorded in previous surveys. However, at the northern end of the Harbour, the abundance and number of species at the four sites near the entrance to the ocean (i.e. sites 2, 3, 12 and 14) were notably lower in the June 2019 survey. The latest survey (Jan 2020) shows an increase in both abundance and the number of species, and this was particularly notable at sites 2 and 3 where the decline was greatest in June 2019.

To further explore the dynamics of faunal communities in the extensive shallow regions of the harbour, in 2018 we conducted a separate survey that focused on sites surveyed in 1996 as part of the Mount Lyell Remediation Research and Demonstration Program sites (Talman et al., 1996). The results of this historical comparison of benthic ecology are described in Appendix 3.

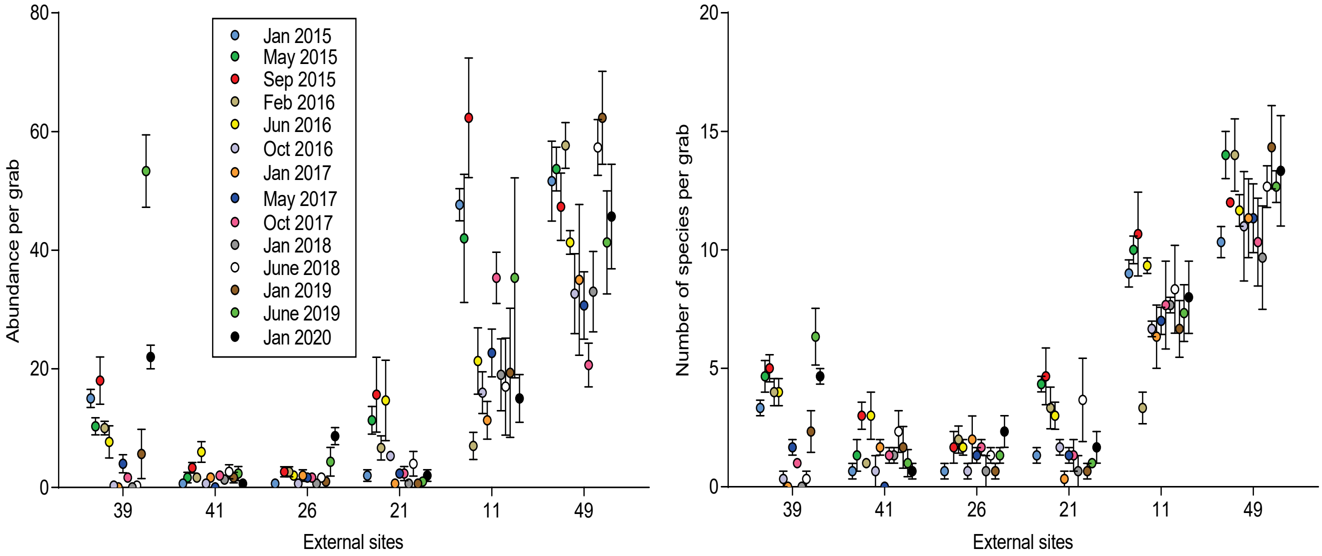


Figure 13 Plots of total infaunal (>1mm) abundance (per grab = ~0.0675m^2) and number of species collected in grabs (n=3) at 7 external sites in Macquarie Harbour from surveys between January 2015 and January 2020. The data for each site represents the mean (±SE) from three replicate grabs. Note: Site 26 not surveyed in May 2015.

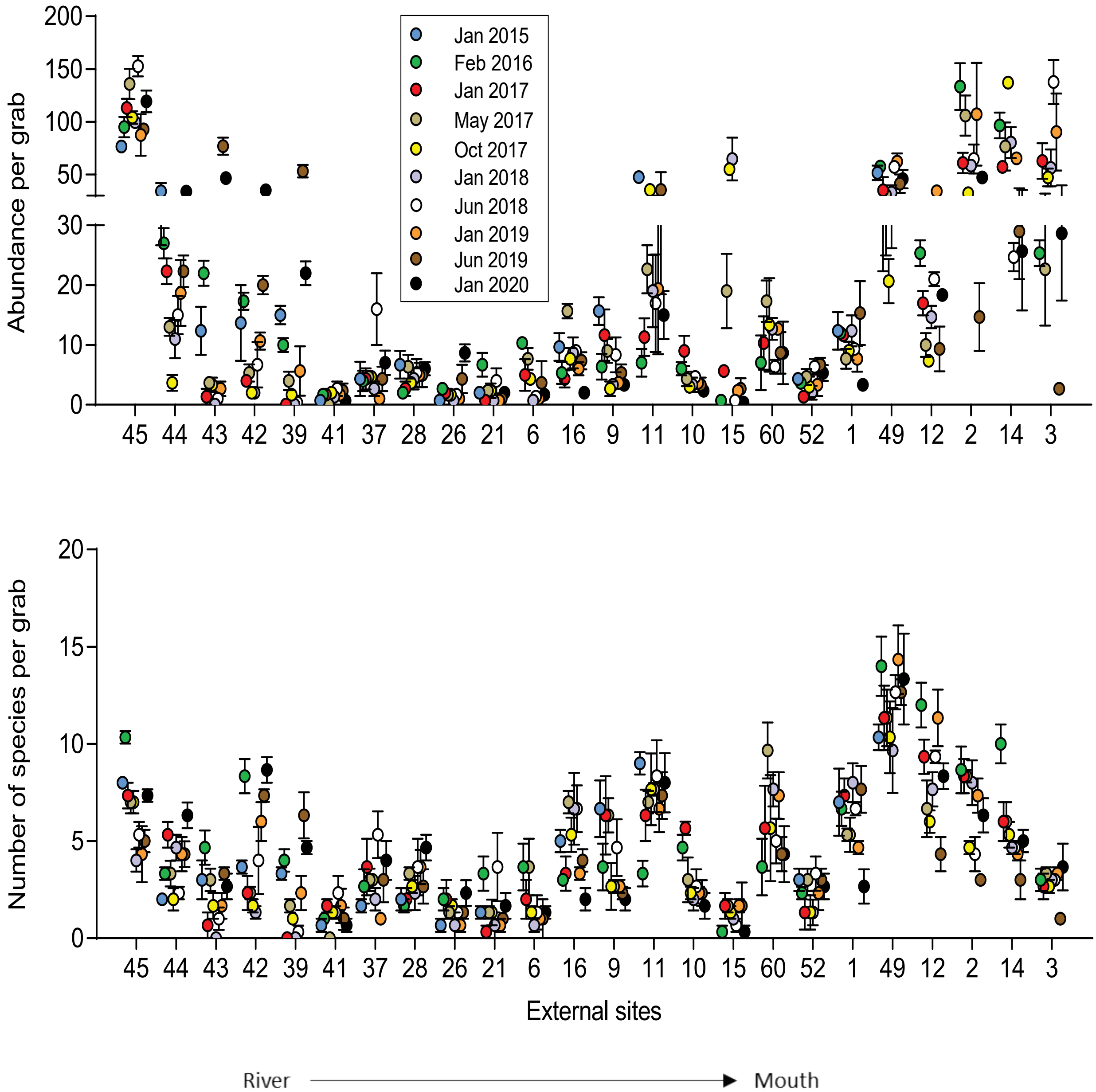


Figure 14 Plots of total infaunal (>1mm) abundance (per grab = ~0.0675m²) and number of species collected in grabs (n=3; bottom panel) at 23 external sites in Macquarie Harbour from surveys in January 2015, February 2016, January 2017 and May 2017, October 2017, January 2018, June 2018, January 2019, June 2019 and January 2020. In the top panel the axis is split to better show differences between surveys at the sites with lower abundances. The data for each lease represents the mean (±SE) from three replicate grabs. Note that sites 2, 3, 10, 14 and 15 were not sampled in the January 2015 survey.

Video Assessments

As part of the ongoing benthic faunal surveys, video assessments of the study sites using an ROV have been conducted in parallel with the infaunal sampling[3]. Three minutes of footage was collected at each site and the footage assessed following the methods described by Crawford et al. (2001). In Macquarie Harbour the scoring categories have been expanded for dorvilleids to provide greater detail on their distribution and relative abundance (Table 2); the scoring categories for *Beggiatoa* are shown in Table 3. Although there was no infaunal survey conducted in the of spring 2018 and 2019, a video assessment of all sites was completed, and the results are presented to provide further insight into temporal changes in the presence of *Beggiatoa* and dorvilleids.

Table 2 Scoring categories of dorvilleid abundance for video assessment

Dorvilleid abundance
0
1-30
31-100
101-300
301-1000
>1000

Table 3 Scoring categories of *Beggiatoa* cover for video assessment

Beggiatoa cover
Absent
Patchy
thick patches
thin mat
thick mat
Streaming

The September 2018 to January 2020 video surveys show that the presence of *Beggiatoa* was low relative to that observed in the October 2016 and January 2017 surveys (Table 4). The occurrence of *Beggiatoa* in this survey (observed on 15 of 51 lease dives) was similar to that observed in 2019; September (14 of 51), June (15 of 51) and January (12 of 21). When present, *Beggiatoa* is most often categorised as patchy, however in the January 2019 and 2020 surveys there were more observations of *Beggiatoa* as a thin mat. At the external sites there has also been little change in the presence of *Beggiatoa* over the same time period; it was noted at 4 of the 28 sites in the January, June and September 2019 surveys, and at 5 of the 18 sites in the January 2020 survey. With the exception of two occasions where thick patchy *Beggiatoa* was noted in January 2019 all other observations at external sites across these surveys have being categorised as patchy (Table 4, Figure 15).

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[3] ROV assessments have generally been conducted within 2-3 weeks of the benthic grab sampling. The ROV assessments are conducted by the 3 growers, and in some cases by Aquenal Pty. Ltd. They are then independently assessed by DPIPWE and EPA.

As we have described in the previous reports, the ROV footage clearly shows an association between the presence of dorvilleid polychaetes and farming (see Table 5, Figure 16). The distribution of dorvilleids typically extends further from the cages than *Beggiatoa*, and dorvilleids are more commonly observed at external sites. In the September 2018 survey dorvilleids were observed on slightly fewer farm dives (61%) than in the two previous surveys - May (69%) and January 2018 (65%). In January 2019 (88%), there was an increase in the presence of dorvilleids on farm dives relative to the previous three surveys; however, their presence in the June 2019 survey decreased to 69% of farm dives. This also corresponded to a decrease in abundance with less observations of the more abundant categories (i.e. > 300 dorvilleids in a dive) and more observations of the lowest category (i.e. 0-30 dorvilleids in a dive). In the September 2019 survey their presence decreased to 51% of farm dives but there was an increase in the more abundant categories, and by January 2020 both presence (76%) and abundance had increased relative to observations in June 2019. This change is largely attributable to their increased presence and abundance at leases 3 and 5 (Figure 16)

At the external sites, dorvilleids were observed on 18% of dives in June 2019 as compared to 61% in January 2019 and 39-43% across the three surveys prior to that. In the June 2019 survey dorvilleids were not observed at the external sites at levels greater than 30 dorvilleids per dive (Table 5, Figure 16). In the two most recent surveys in September 2019 and January 2020 dorvilleids were observed on 18 and 36 % of external dives respectively, the majority of which were observations of the lowest category (i.e. 0-30 dorvilleids in a dive).

Ross et al. (2016) noted that the broader distribution is largely associated with the dorvilleid *Schistomeringos loveni,* which appears to be less tolerant of highly enriched sediments than the colony forming dorvilleid *Ophryotrocha shieldsi* that is typically found closely associated with stocked cages. Colonies were observed on less dives in September 2019 (1 of 79 dives) and January 2020 (2 of 79 dives) compared with the previous two surveys in June 2019 (3 of 79 dives) and January 2019 (6 of 79 dives). All these observations were on leases, near the cages and not at external sites. The broader distribution of dorvilleids seen in Figure 16 is still largely associated with *Schistomeringos loveni* and reflects its preference for more moderately enriched sediments.

Table 4 Percentage of lease and external sites for each category of Beggiatoa cover for each survey.

		N	absent	patchy	thick patchy	thin mat	thick mat	streaming
Jan-15	External	25	100%					
	Lease	87	80%	10%	1%	8%		
May-15	External	6	100%					
	Lease	30	63%	23%	3%	3%	7%	
Sep-15	External	19	89%	11%				
	Lease	41	73%	2%		17%	7%	
Feb-16	External	28	86%	14%				
	Lease	41	73%	12%		10%	5%	
Jun-16	External	19	79%	21%				
	Lease	41	66%	15%		10%	10%	
Oct-16	External	18	72%	33%				
	Lease	42	52%	12%	7%	10%	17%	
Jan-17	External	28	75%	21%		4%		
	Lease	51	43%	25%		12%	16%	4%
May-17	External	28	96%	4%				
	Lease	51	63%	12%	2%	14%	10%	
Sep-17	External	28	93%	7%				
	Lease	51	71%	8%	2%	10%	10%	
Jan-18	External	28	96%	4%				
	Lease	51	59%	25%		8%	8%	
May-18	External	28	89%	11%				
	Lease	51	59%	33%	2%	6%		
Sep-18	External	28	86%	14%				
	Lease	51	61%	22%		8%	6%	4%
Jan-19	External	28	86%	7%	7%			
	Lease	51	75%	12%	2%	10%		2%
Jun-19	External	28	86%	14%				
	Lease	51	71%	24%	4%	2%		
Sep-19	External	28	86%	14%				
	Lease	51	73%	22%		4%	2%	
Jan-20	External	28	82%	18%				
	Lease	51	71%	16%	2%	10%	2%	

Table 5 Percentage of lease and external sites for each category of dorvilleid abundance for each survey.

		N	0	0-30	30-100	100-300	300-1000	>1000
Jan-15	External	25	44%	32%	12%	8%	4%	
	Lease	87	14%	8%	10%	3%	17%	47%
May-15	External	6	100%					
	Lease	30	10%	33%	10%	27%	17%	3%
Sep-15	External	19	79%	21%				
	Lease	41	37%	17%	15%	2%	12%	17%
Feb-16	External	28	43%	39%	7%	11%		
	Lease	41	27%	20%	7%	5%	20%	22%
Jun-16	External	19	84%	16%				
	Lease	41	44%	32%	2%	10%	5%	7%
Oct-16	External	18	53%	16%	11%	5%	11%	5%
	Lease	42	37%	32%	12%	7%	7%	5%
Jan-17	External	28	57%	11%	11%	14%	7%	
	Lease	51	33%	16%	12%	25%	12%	2%
May-17	External	28	50%	29%	14%	4%	4%	
	Lease	51	18%	24%	10%	18%	24%	8%
Sep-17	External	28	68%	18%	11%	4%		
	Lease	51	20%	10%	18%	24%	16%	14%
Jan-18	External	28	61%	18%	14%	7%		
	Lease	51	35%	24%	12%	14%	12%	4%
May-18	External	28	61%	39%				
	Lease	51	31%	22%	22%	16%	8%	2%
Sep-18	External	28	57%	43%				
	Lease	51	39%	29%	14%	10%	6%	2%
Jan-19	External	28	39%	50%	11%			
	Lease	51	12%	18%	25%	18%	10%	18%
Jun-19	External	28	82%	18%				
	Lease	51	31%	39%	6%	16%	2%	6%
Sep-19	External	28	82%	18%				
	Lease	51	49%	20%	4%	6%	10%	12%
Jan-20	External	28	64%	25%	11%			
	Lease	51	24%	27%	14%	6%	14%	16%

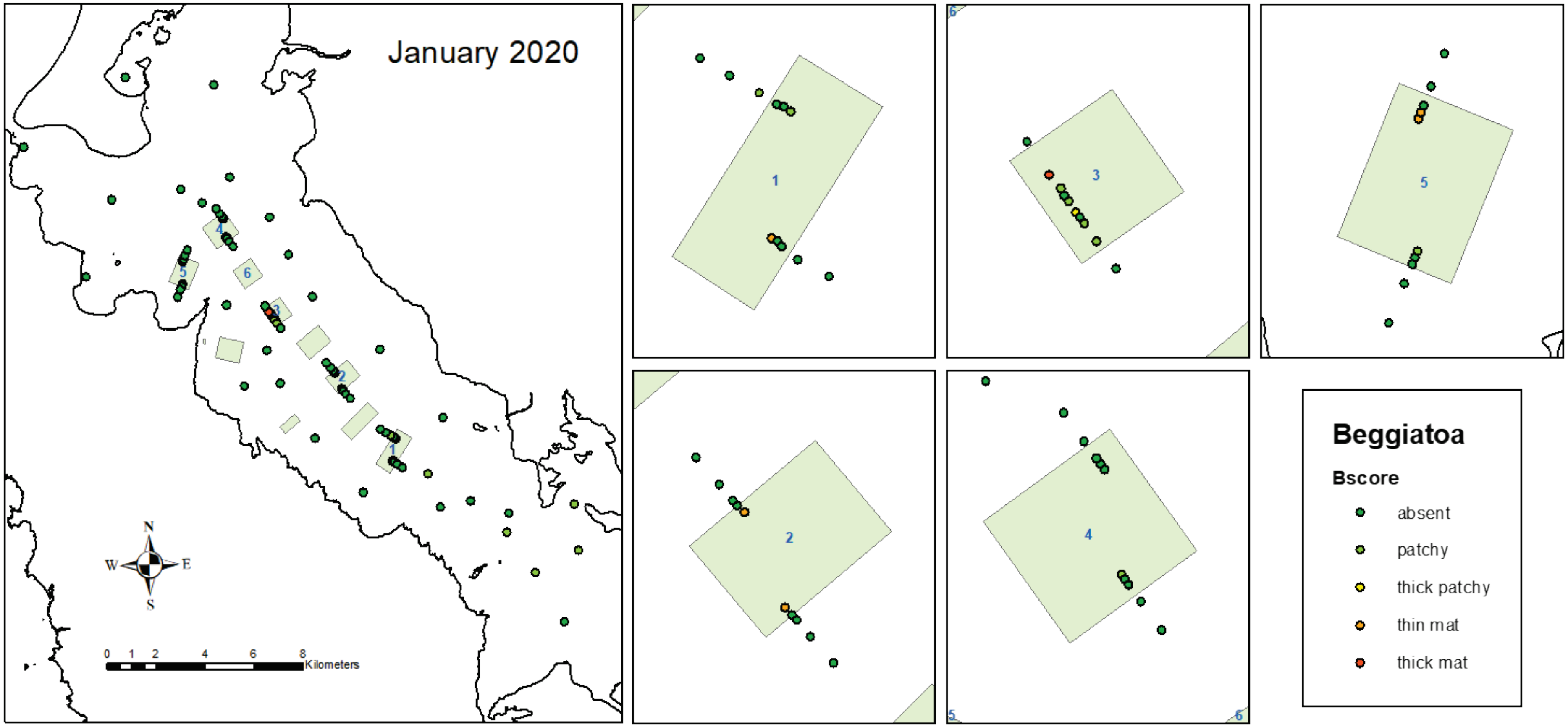

Figure 15 *Beggiatoa* score (severity) from ROV footage at study sites across the harbour on the left panel and shown in more detail for each of the study leases in the panels on the right.

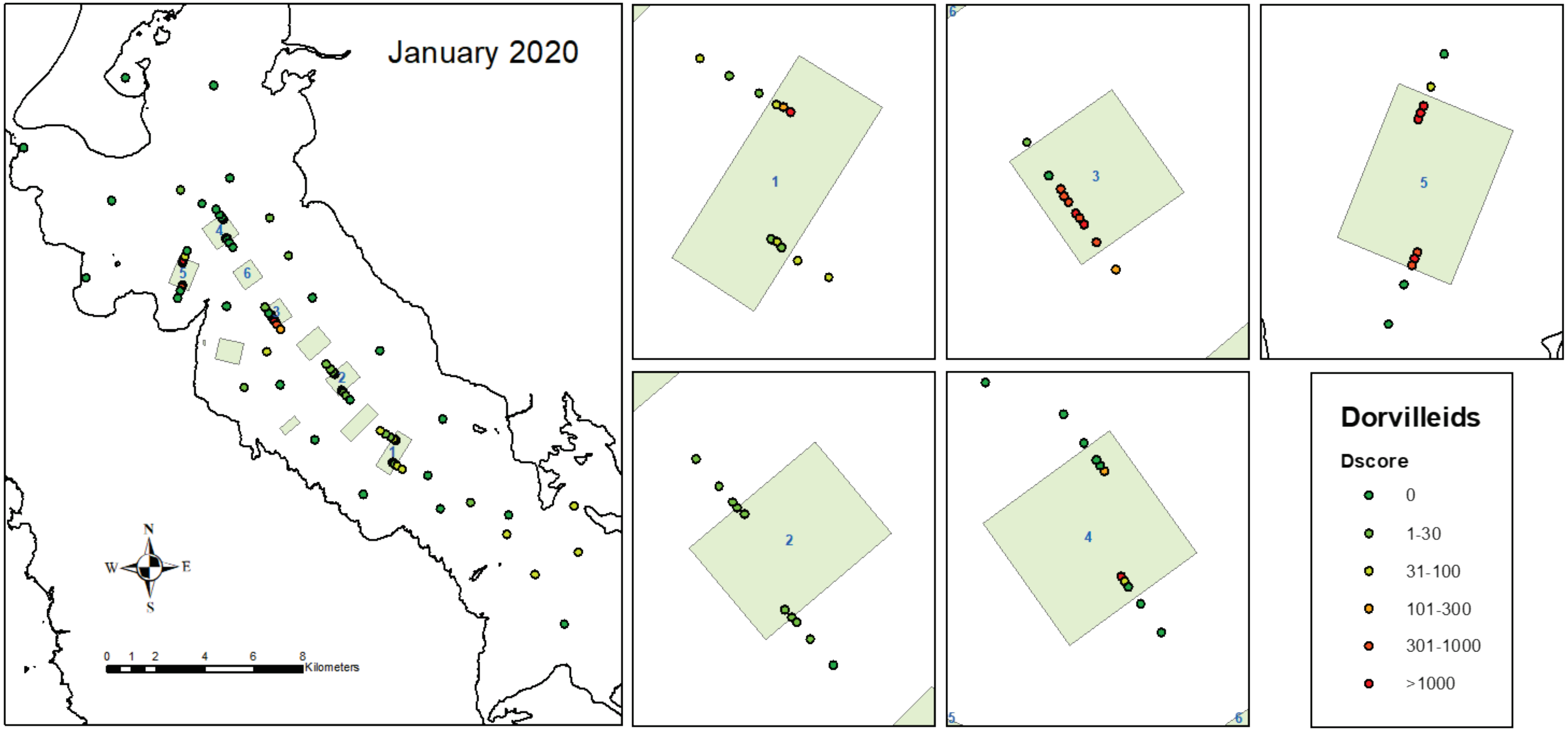

Figure 16 *Dorvilleid* score based on counts from ROV footage at study sites across the harbour on the left panel and shown in more detail for each of the study leases in the panels on the right.

Recommendations

The present study has substantially enhanced our understanding of benthic conditions in Macquarie Harbour, and the drivers and importance of oxygen dynamics. Recommendations are broken down into three key areas:

Benthic ecology

The regular benthic surveys have been critical in understanding how the biology and ecology of the harbour sediments respond to farming and dissolved oxygen conditions at both lease and harbour scales. The results have shown improved conditions over recent years and the recovery of harbour wide external sites to well within the range reported before the decline in spring 2016 – early 2017. At the lease scale, the research has highlighted the capacity of faunal recovery via recruitment from the shallower reaches of the harbour. However, the results also highlight the critical role and interplay of bottom water dissolved oxygen conditions experienced at the lease level, and the importance of farm management in determining benthic conditions and recovery dynamics. We recommend that surveys of the harbour wide sites, including several outer (e.g. 250 & 500 m) transect sites in the deeper sections of the harbour, are maintained to monitor harbour health as part of the MHEMP monitoring program, but that these can be undertaken less frequently than conducted during the research project (i.e. every 1-2 years cf. quarterly/ biannually). At the lease scale, the findings of this project and FRDC 2015-024 found a good relationship between sediment health visual assessments using ROV and benthic condition data, and as such we recommend that ROV visual assessments are maintained at their current frequency (biannual) to monitor lease benthic conditions. It is also important to acknowledge that whilst the current study has focused on sediment faunal communities, larger fauna from higher trophic levels may provide a holistic indicator of harbour health. As such, we recommend longer term monitoring of harbour health include a focus on species such as the endangered Maugean Skate, which is now known to be sensitive to environmental change in the harbour (Moreno et al., 2020)

Monitoring

The development of the real time DO observation network in the harbour has been instrumental in monitoring and understanding DO dynamics for farm managers, regulators, and researchers. There are now multiple, and often overlapping monitoring programs measuring DO (and other parameters) across industry, government, and research. An important next step will be to optimise integration across the parallel sampling programs.

Modelling

The detailed recommendations can be found in Wild Allen et al (2020), but are summarised here:

- Installation of river flow gauges in the lower reaches of the Franklin-Gordon and King-Queen River catchments, more regular maintenance of the Strahan tide gauge and mapping of entrance bathymetry are recommended to improve the accuracy of the models.
- Improve forecasting capability of model via i) ensemble model forecasting (using the available range of BoM model forecasts), ii) data assimilation of near real time data sets, iii) a catchment model (including predicted dam releases) and iv) an automated alert system to improve appropriate forecast delivery.

- Additional model scenarios to better characterise the impact of contrasting anthropogenic loads and seasonal dam releases on water quality
- Extension of the analysis of model results (including use of remote sensing) to incorporate west coast shelf environment

Extension and Adoption

The current project has been disseminated to resource managers, industry and the broader public in the following ways:

- Comprehensive IMAS update reports (8 in total) on the status of dissolved oxygen and benthic conditions in the harbour based on the latest research observation have been released publicly through 2017-2020
- Creation of a documentary 'Listening to the Harbour' which describes the important natural features of Macquarie Harbour, the environmental responses to salmon farming, and the role that science has played and is playing in determining an ecologically sustainable level of farming into the future. YouTube video has to date been viewed over 2000 times and is used by the tourism industry on the west coast to inform both locals and visitors

  https://www.youtube.com/watch?v=f5peYJrBw_Q

- The outputs of the research project have played a key role in informing decision making both for government, research and industry. The reports are highly cited in the EPA biomass determinations for the harbour https://epa.tas.gov.au/regulation/salmon-aquaculture/macquarie-harbour/management-determinations
- The findings of the research have been presented at several public forums in Strahan and elsewhere, and the research team have contributed to numerous print, television and radio interviews, including several live interviews on ABC Mornings with Leon Compton
- The project investigators have also presented the results at several national and international scientific conferences, and various components of the data are currently being prepared for publication in peer reviewed scientific journals

Appendix 1: References

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Appendix 2: Macquarie Harbour oxygenation: a paleo-perspective

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[2] School of Environment, University of Auckland

Background information, methods and results:

The decline bottom and mid water oxygen levels in Macquarie harbour (MH) over the past decade has received much attention, and the links to sediment health have been well described above. To put the recent decline in context we have monitoring records of water column oxygen levels back to the early 1990s. The purpose of this pilot study was to use the sediment record to understand the history of oxygenation/deoxygenation events in MH over a much longer, geological period.

Unlike atmospheric gases, which can be preserved in bubbles trapped in icesheets, seawater and the gases it contains like oxygen are not preserved through time. However, variations of redox sensitive element concentrations in the sediments, such as Uranium (U), Rhenium (Re) and Manganese (Mn), have been widely used as proxies to detect past oceanic oxygen changes (Algeo, Morford, & Cruse, 2012; Colodner, 1991; Durand et al., 2018; Morford & Emerson, 1999). Manganese, U and Re solubilities in seawater vary with the dissolved oxygen concentration of the seawater. When the oxygen concentration of seawater decreases, U and Re are reduced from their soluble forms ($UO_2(CO_3)3)^{4-}$, $U(OH)_4$, and ReO^{4-}) toward insoluble forms (UO_2 and $ReO_2.2H_2O$). This causes U and Re solid phases to accumulate in the sediments. In other words, when the concentration of dissolved oxygen in the water overlaying the sediment bed decreases, the concentrations of U and Re in sediments increase (Figure 17). An opposite relationship to the one described for U and Re exists for Mn: the higher the dissolved oxygen concentration, the higher the concentration of Mn in the sediments. This signal is then preserved and can be used as a proxy to reveal past oceanic oxygen changes. However, it is important to note that Mn, U and Re concentrations in sediments reflect oxygenation changes at the sediment water interface, and as such do not reveal changes in oxygenation of surface waters.

To reconstruct the oxygenation history of MH during the past thousand years, we used the approach detailed above in sediment cores, namely from site MC (Figure 18, site MA data were pre-existing to this study). MC is one of nine cores previously taken using a Mackereth corer by Dr Paul Augustinus. These nine cores were originally taken to study mine run-off pollution in MH. MC sediments were stored at Geosciences Australia and made available for this oxygenation study. Once MC's sediments were divided in depth sections and dried, the precise quantification of the core's redox element contents was achieved using a wet-chemistry approach (Durand et al., 2016). The sediment samples were completely digested in a cocktail of acids. The content of the digest was then analysed by Inductively Coupled Plasma-Mass Spectrometry at the Central Sciences Laboratory (CSL, University of Tasmania) to determine the concentrations of redox elements and thus the oxygenation variations.

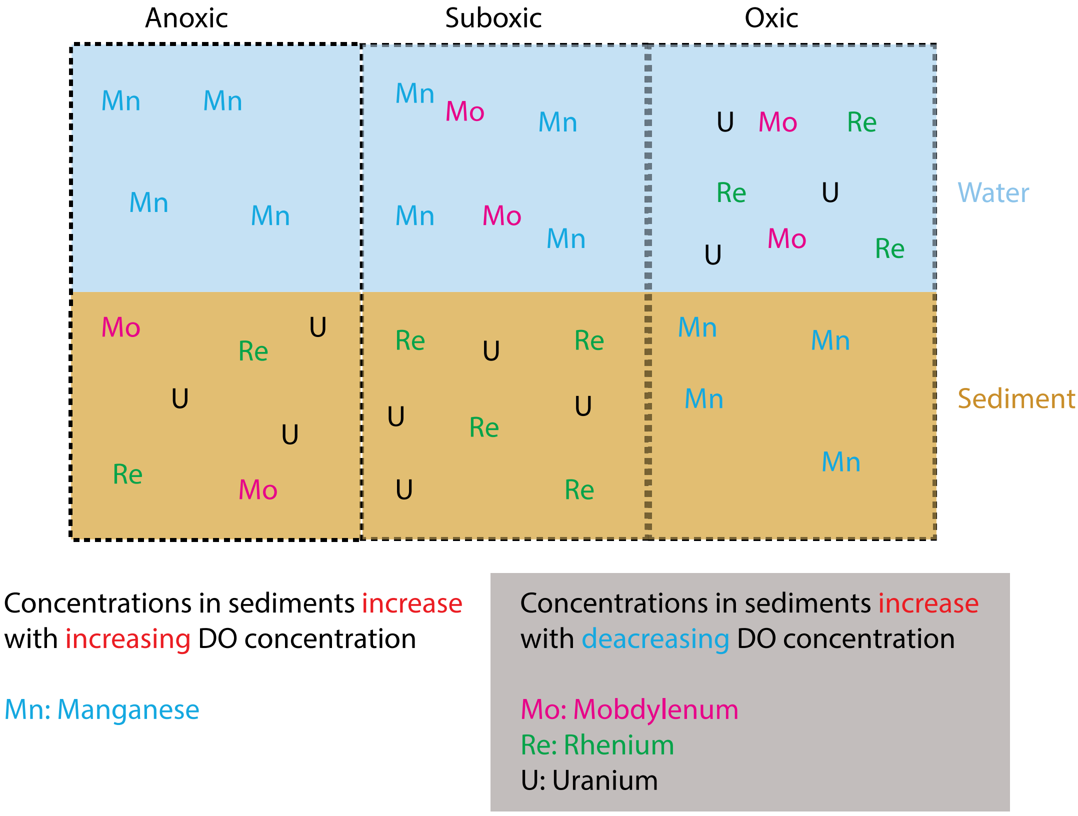


Figure 17 Summary of the conditions leading to Mn, U and Re enrichment in sediments

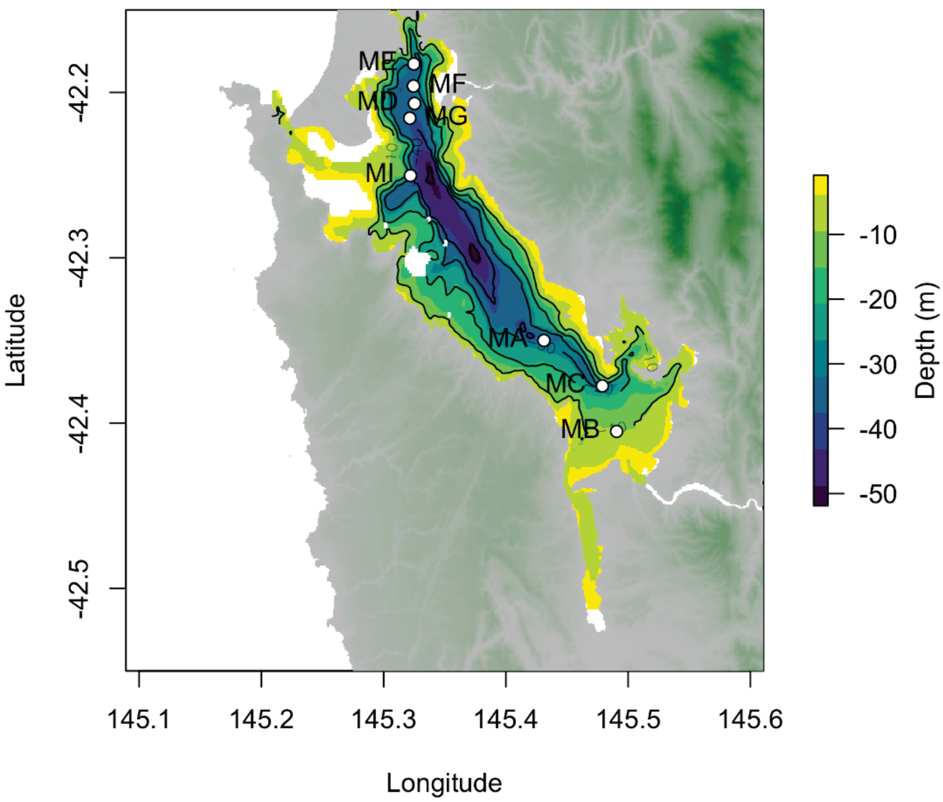


Figure 18 Locations of the cores collected from Macquarie Harbour (MA to MI).

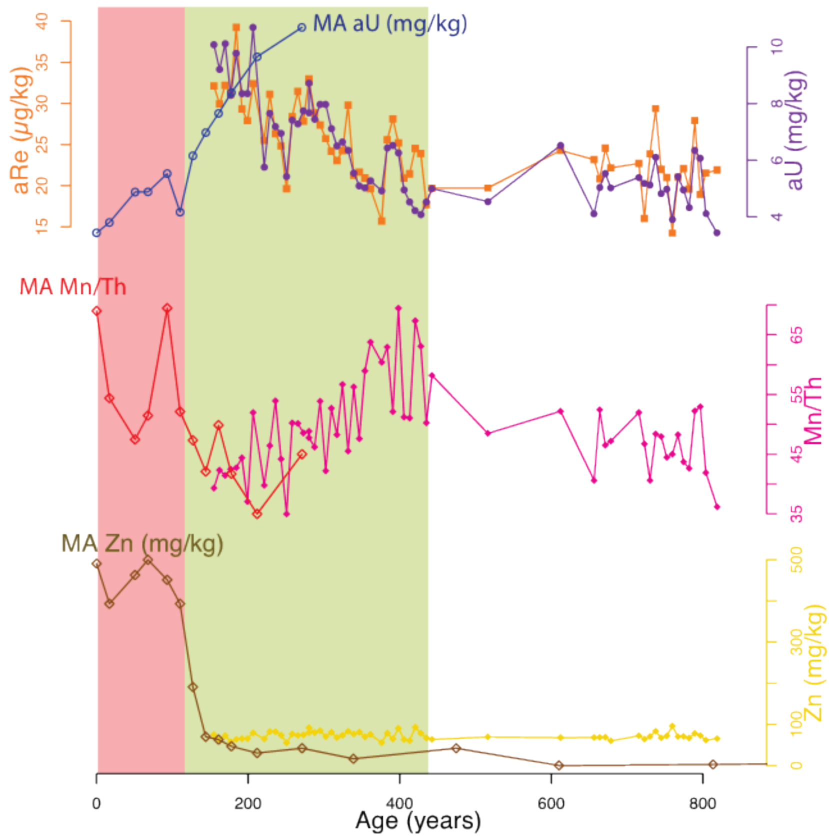


Figure 19 Variations of authigenic Uranium (aU), Rhenium (aRe), Manganese/Thorium (Mn/Th) and Zinc (Zn) in two sediment cores (MA open symbols and MC filled symbols) from Macquarie Harbour. Green shading highlights the deoxygenation event observed, while red shading highlights potentially compromised data because of mine tailing contamination. Authigenic fractions were used to remove the lithogenic component from the U and Re variations observed. For the same reason the ratio Mn/Th was represented instead of Mn concentrations.

The concentrations of Re and U co-varied extremely well in MC. Early in the record, between 800 and 400 years ago, the Re and U concentrations were relatively constant before a gradual increase started 400 years ago, reaching its peak 200 years ago. The concentrations of U in MA (Figure 19) were also at their maximum around a similar time as MC and decreased from 200 years ago until now. Overall, the variations of Mn in MA and MC followed the opposite pattern to that seen for Re and U. The concentrations of Zinc (Zn) in MA and MC remained low through the record till about 100 years ago when a sharp increase was observed.

The variations of Manganese (Mn), Uranium (U) and Rhenium (Re) in two sediment cores (MA and MC) suggest that a large deoxygenation event started roughly 400 years ago and progressed to its maximum, around 200 years ago, before subsiding since then (Figure 19). However, mine run-off contamination has the potential to contaminate the sediments and compromise the results from this study. Zinc (Zn) concentrations in the sediment is used here as a proxy for the influence of mine tailings. When considering the record beyond 100 years ago, Zn concentrations were low and did not co-vary with the other elements providing confidence in the reconstructed record of oxygenation/deoxygenation for that period. However, elevated concentrations of Zn in the records for the last 100 -150 years compromise the interpretation of the apparent reoxygenation over this period (Figure 19). In other words, because mine run-offs have contaminated the sediments of MC going back 100-150 years, we cannot be certain that the reoxygenation observed is not a result of this contamination. The mine run-off contamination observed in the more modern part of our record also prevents us from comparing oxygen levels at the peak of the deoxygenation event to present ones.

The data from the pilot study provides a time series of oxygen change; however, the proxies used do not allow for a reliable estimate of the actual dissolved oxygen concentration in MH during the deoxygenation event ~ 200 years ago. This is because the relationship between Mn, U and Re solubilities and dissolved oxygen is not linear; the precipitation of Mn, U and Re solid phases occurs only when a redox threshold is reached. Therefore, Mn, U and Re can only be used as proxies for oxygenation change and not absolute concentrations.

Because the sediment data does not provide an estimate of oxygen concentration it is difficult to put the current decline in context, and more so, given differences in the temporal resolution of the data provided in each data set. The sediment record is it a decadal scale at best over nearly 800 years, whereas the contemporary monitoring covers the last three decades and has evolved from monthly (mostly quarterly from 1993-2011) to daily, and with the advent of real time sensors, minutes in recent years. This is important, given that the rate of change is likely to be critically important in determining the response and resilience of the harbour ecology. The deoxygenation event highlighted in the sediment cores lasted many decades, and the high variability of the Mn, U and Re concentrations over the whole record suggest that oxygenation of MH varies significantly.

Appendix 3: Historical comparison of benthic ecology

Jeff Ross, Adam Davey, Jimmy Hortle, Andrew Pender, Jason Beard and Aine Nicholson

One of the challenges when interpreting contemporary patterns in benthic ecology in many systems, including Macquarie Harbour, is the ability to contextualise observations where there are limited historical data. To assess how benthic communities have changed since farming began in Macquarie Harbour, both broadly in the harbour and in direct response to farm derived organic enrichment, Ross et al., (2016) compared the results of benthic surveys of harbour and lease sites undertaken in early 2015 against baseline surveys of farm and external sites conducted between 1999-2003 and in 2012. Because of differences in site locations and farming activity, a similar number of sites with a comparable distribution (e.g. depth range) were selected to minimise any potential biases when comparing between surveys. The comparison with baseline surveys highlighted a change in the broader benthic ecology over the past 15 years, with arguably the greatest change occurring in the last 2 years, as demonstrated by a measurable increase in total abundance, species richness and species diversity. These observed changes have had an influence at a functional level, with a decrease in burrowing taxa and an increase in the more static suspension and deposit feeding tube builders. Whilst there could be a range of explanations for this change, such as a recovery from the effects of mining or changes in the regulation of catchment inflows influx of organic matter associated, the authors concluded that it is highly likely that the addition of nutrients and organic matter from fish farming has played a role in stimulating benthic productivity.

The report also noted that whilst the selection of comparable sites across surveys was valuable, there was limited capacity to identify changes beyond the deeper central harbour region where most of the farming now takes place. As part of the Mount Lyell Remediation Research and Demonstration Program, a major survey of the benthic invertebrate communities was conducted at sites throughout the harbour in 1996 by Talman et al (1996), following a pilot survey by O'Conner et al., (1996) in 1995 (Figure 20). This data wasn't included in the historical comparison by Ross et al. (2016) because of a lack of overlap in specific study areas; the Talman survey was focused in the shallower regions of the harbour (see Figure 20). The surveys conducted in FRDC 2016-067 highlighted significant spatial and temporal variability in the faunal assemblages found throughout the deeper central region of the harbour. This raised a number of questions about the extent of any impacts, and in particular the potential effects on the faunal communities in the extensive shallow regions of the harbour. For example, has the benthic ecology of the shallower regions of the harbour changed, and do the shallower communities possibly provide an important reservoir for recruitment and recovery of benthic communities in the deeper regions. Consequently, we undertook an additional survey of sites in these shallower regions in 2018, where we sought to align the sites and contrast the results against the 1996 benthic survey sites (Talman et al., 1996) and a more recent survey of the WHA sites conducted in 2015 (Barrett et al. 2016), with 39 sites sampled in total.

The results indicated that average abundance was higher (2018: 77 ± 26 1996 38 ±14 ind. per grab) and species counts slightly lower in 2018 (4.1 ± 0.4 species per grab) compared to 1996 (4.8 ± 0.5 species per grab) (Figure 21). In 2018, two sites were found to contain no fauna (sites 3 and 5 near the mouth of the King River), abundance elsewhere varied up to a maximum of 862 individuals at site 25 towards the southern end of the harbour. In 1996 there were no individuals recorded from sites 2, 3, 4 and 39, again all near the mouth of the King River, and in this instance the maximum was 573 individuals at site 33 again in the southern reaches of the harbour (Figure 22). It is well known that the Harbour is quite naturally depauperate (e.g. Edgar et al. 1999), with only a maximum of 12 species per sample (site 38) reported in 2018, which contrasts quite well with 1996 where up to 10 species per sample were reported (site 37).

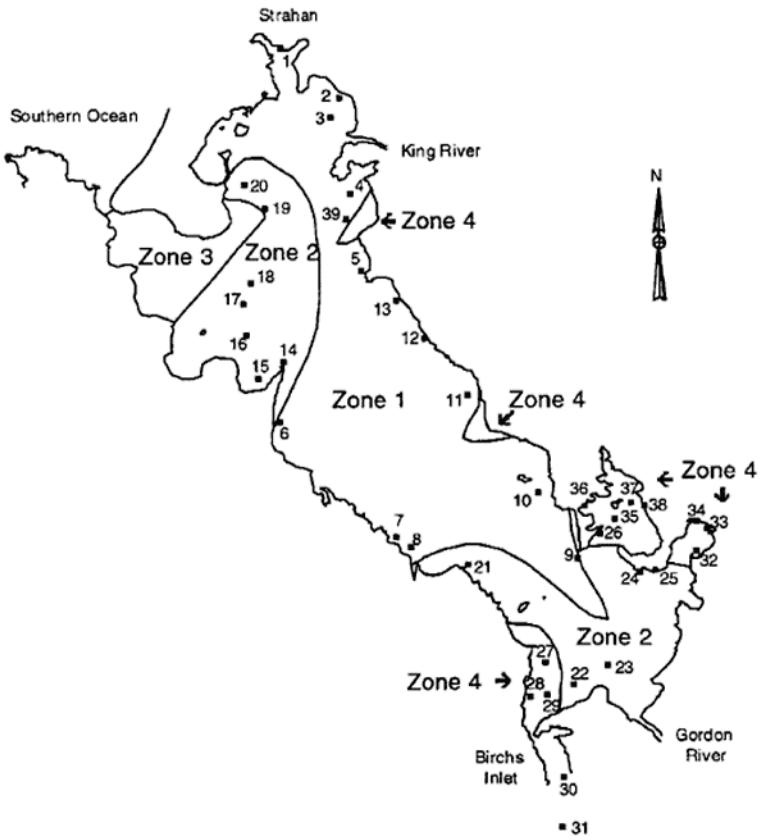


Figure 20 Sample sites within zones in Macquarie Harbour. Sample sites were allocated into the same zones as used in the 1996 survey (Talman 1996); the 1996 survey was focused on characterising the effects of heavy metals on the benthic ecology. These zones were based on sediment copper concentrations recorded in 1993 and defined by Koehnken (1996).

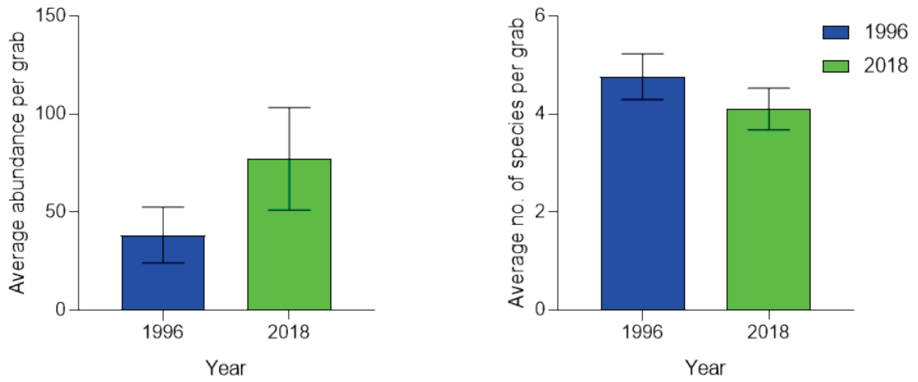


Figure 21 Average abundance and number of species per grab in the 1996 and 2018 surveys pooled across sites.

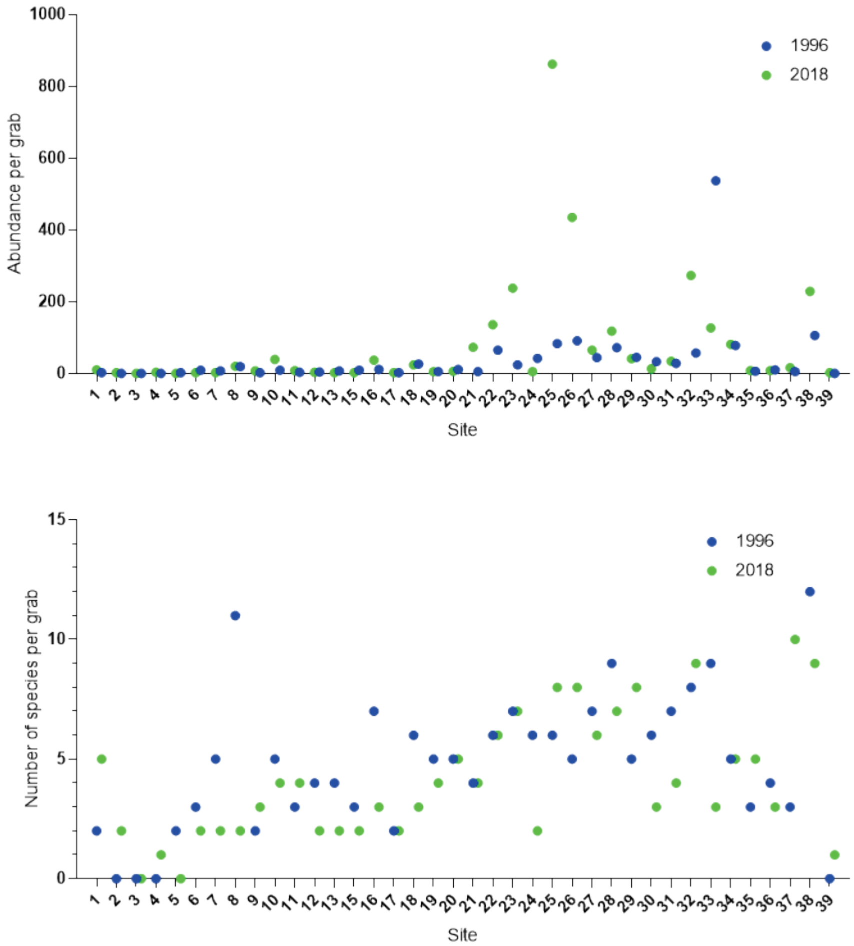


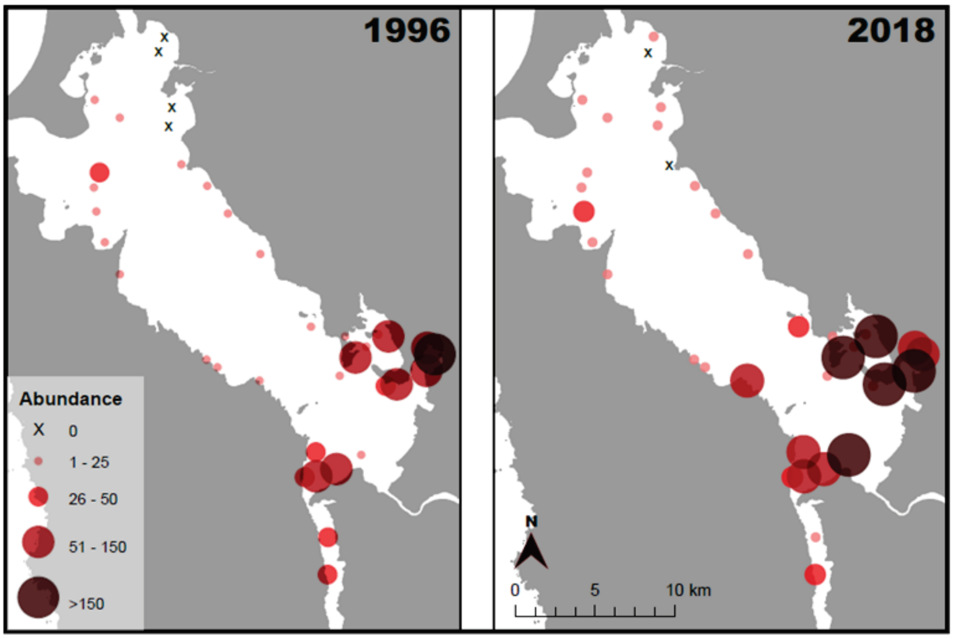
Figure 22 Abundance and species counts at individual sites in 1996 and 2018.

The spatial distribution maps in Figure 23 clearly show that the greatest increase in abundance was seen at the sites in the southern harbour and closest to the WHA. It is also perhaps noteworthy that in the 2018 survey, fauna, albeit in low numbers, was recorded at three of the five sites directly adjacent to the entrance of the King River whilst in the 1996 survey fauna was observed at only one of these sites.

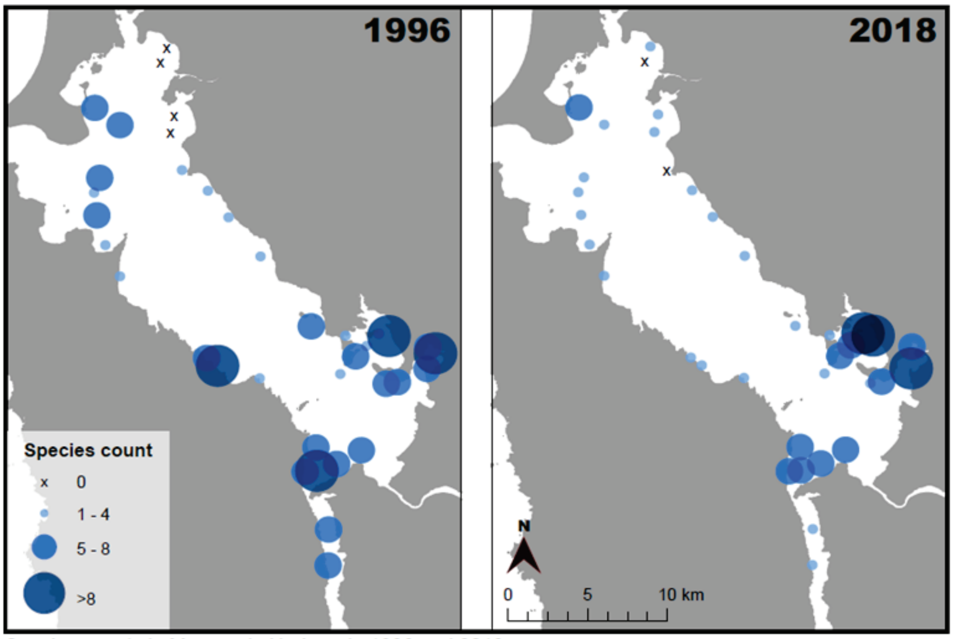
From the multivariate ordination (Figure 24) it is possible to see some consistency in the faunal composition and distribution patterns between the 1996 and 2018 surveys as well as some quite clear differences. The upper estuary sites in the World Heritage area are largely grouped to the left of the ordination and were characterised by species indicative of brackish / estuarine conditions consistent with expectations for these shallow sites in the southern reaches of the harbour (i.e. the small bivalve *Arthritica semen*, mussel *Xenostrobus secures,* gastropod *Tatea rufilabris*, orbiniid polychaete *Scoloplos normalis*, estuarine crab *Amarinus laevis*, amphipod *Paracorophium* sp 1). A number of these species were more abundant in the 2018 survey. Not surprisingly we can also see the tight clustering of sites in the vicinity of the outflow from the King River that had little/ no fauna.

For the remaining sites throughout the harbour the ordination does tend to suggest there has been a change in the faunal composition between surveys, with the 1996 samples lying consistently below and to the right of those from 2018 on the plot. This data has yet to be explored in detail, however, preliminary analysis looking at overall sample similarity (SIMPER; PRIMER 6) suggests that the main differences reflect an increase of the small bivalve *Arthritica semen*, the gastropod *Tatea rufilabris* and the amphipod *Paracorophium* sp 1 and a decrease in the abundance of the amphipod *Limnoporeia yarrague,* mysid *Haplostylus sp.* and orbiniid polychaete *Leitoscoloplos bifurcatus* in 2018 compared with 1996 (Figure 24 & 25).

It is important to note that all these species can be highly variable in numbers in estuarine systems, both spatially and temporally, and therefore these differences are not necessarily unusual or significant. In fact, when we include data from the survey in 2015 (Barrett et al., 2016) and focus just on the WHA sites, the abundance and species counts across the three surveys are not significantly different and there was no clear or consistent either spatially or temporarily (Figures 26 - 29). With only two sampling points it is not possible to definitively determine whether the broader changes between surveys observed in the faunal communities from the shallow sites in the central and northern parts of the harbour reflect a longer term shift in the benthic ecology or are natural temporal fluctuations between surveys; additional surveys in future years would help establish this more clearly.



Species abundance in Macquaire Harbour in 1996 and 2018



Species counts in Macquarie Harbour in 1996 and 2018

Figure 23 Spatial distribution of abundance and species counts throughout the harbour in the 1996 and 2018 surveys.

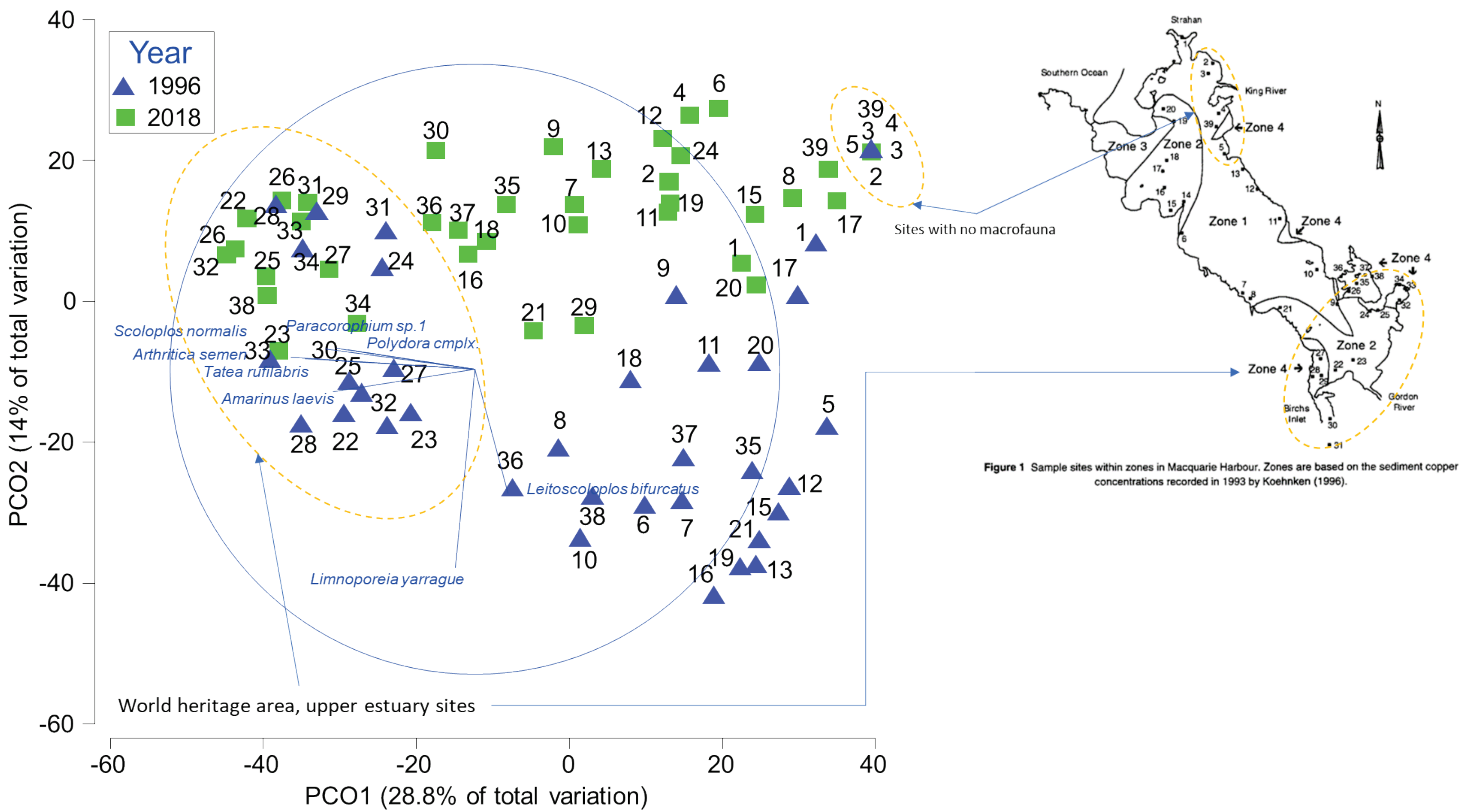


Figure 24 Principal Coordinate analysis comparing benthic communities from 1mm-sieved grab samples in 1996 and 2018. Species shown have a 0.4 correlation.

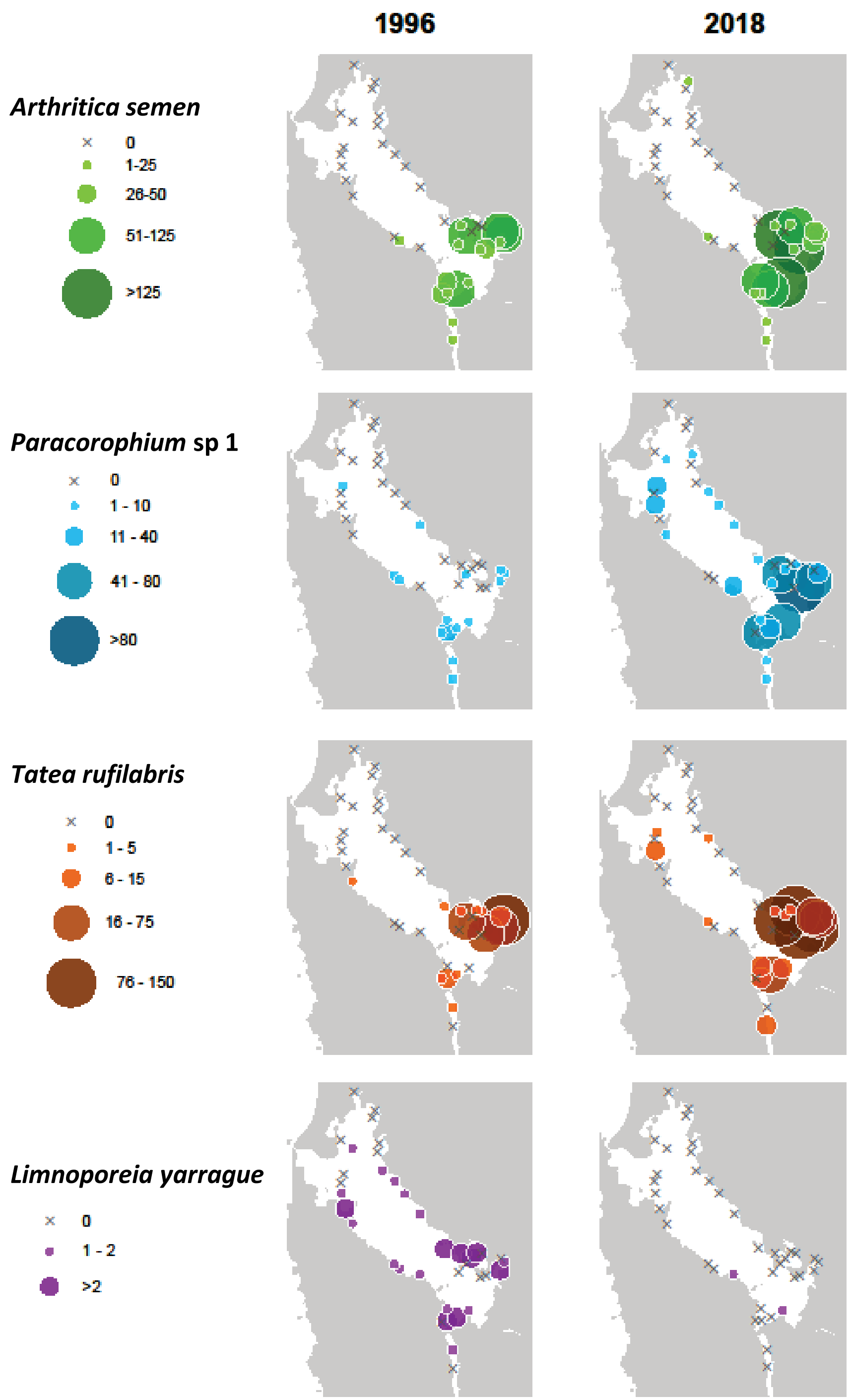


Figure 25 Spatial distribution of four of the most abundant taxa in the 1996 and 2018 surveys

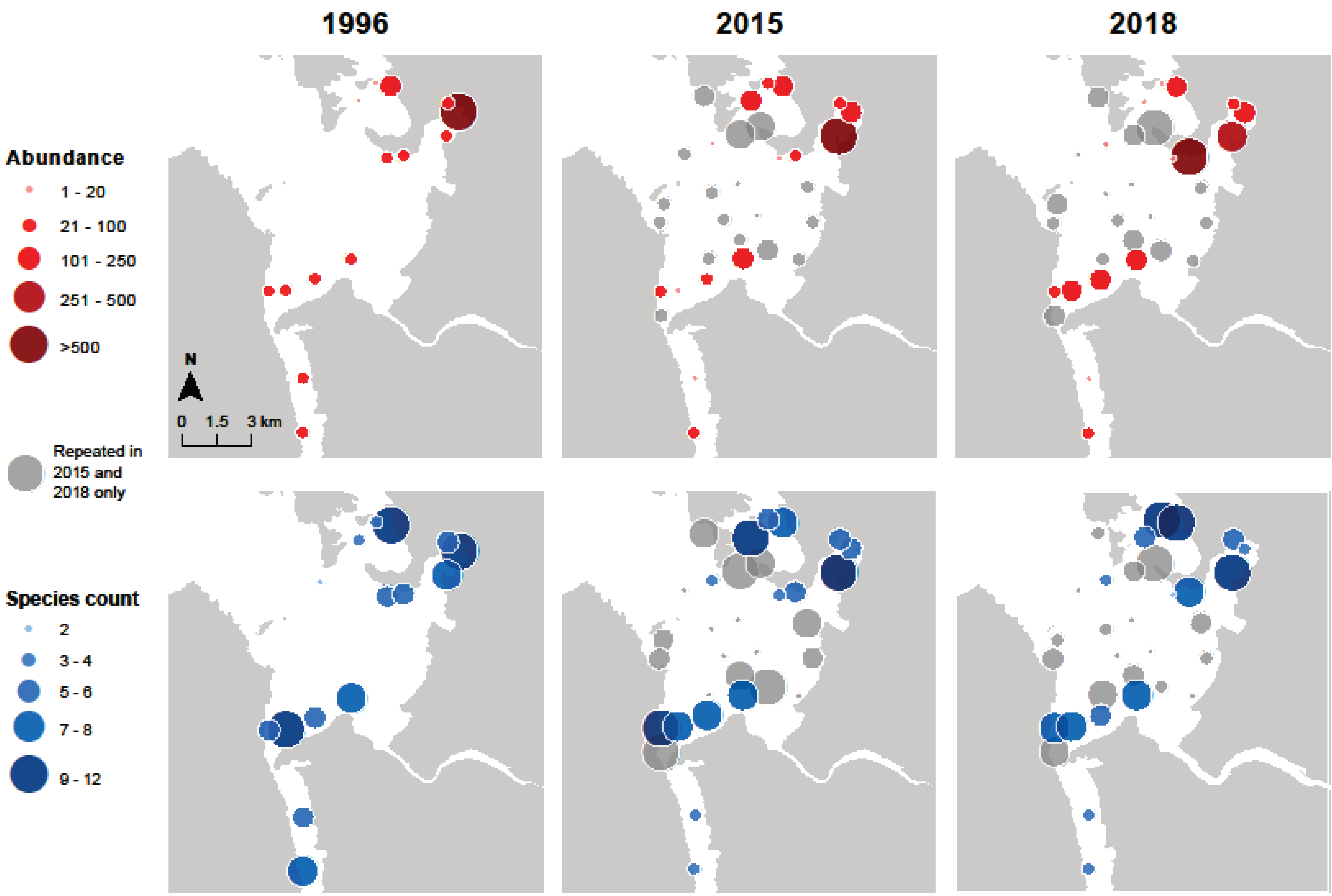


Figure 26 Spatial distribution of abundance and species counts throughout the harbour in WHA in 1996, 2015 and 2018 surveys. Note, the deeper sites (grey) were only sampled in 2015 and 2018.

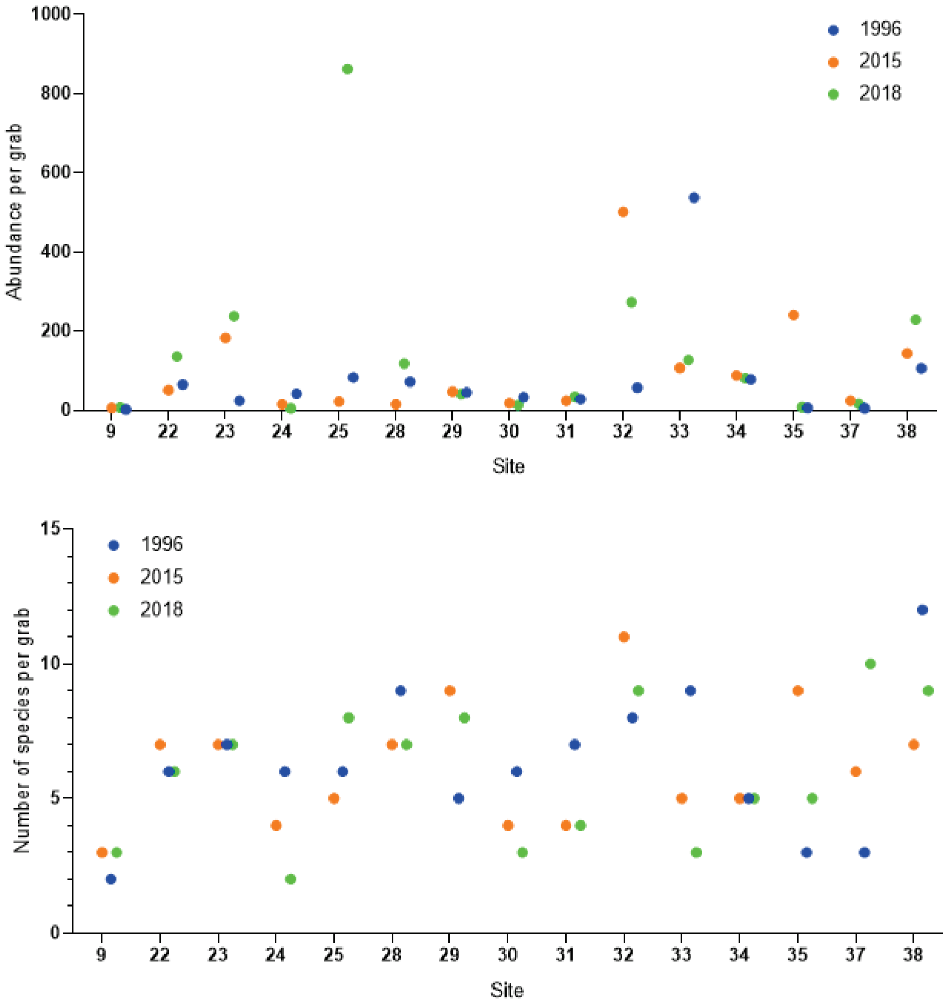


Figure 27 Abundance and species counts at the WHA sites sampled in 1996, 2015 and 2018

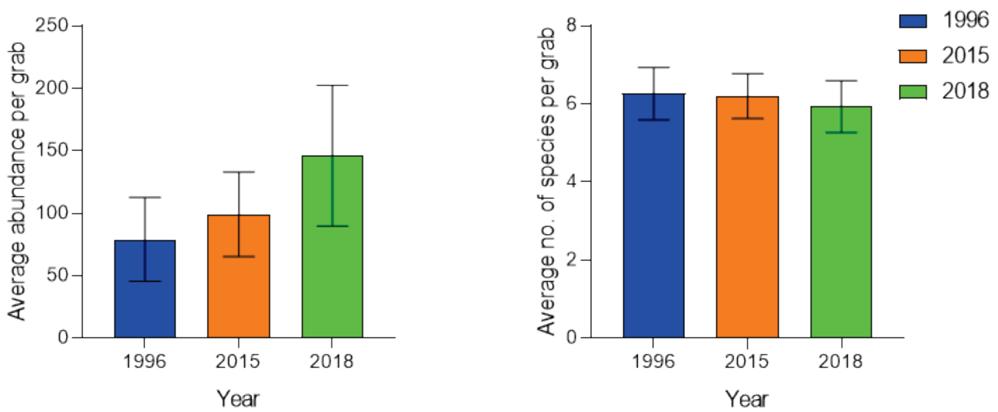


Figure 28 Average abundance and number of species per grab, pooled across the WHA sites in the 1996, 2015 and 2018 surveys. Note this only includes the sites that overlapped all three surveys and thus represents the shallower regions of the WHA

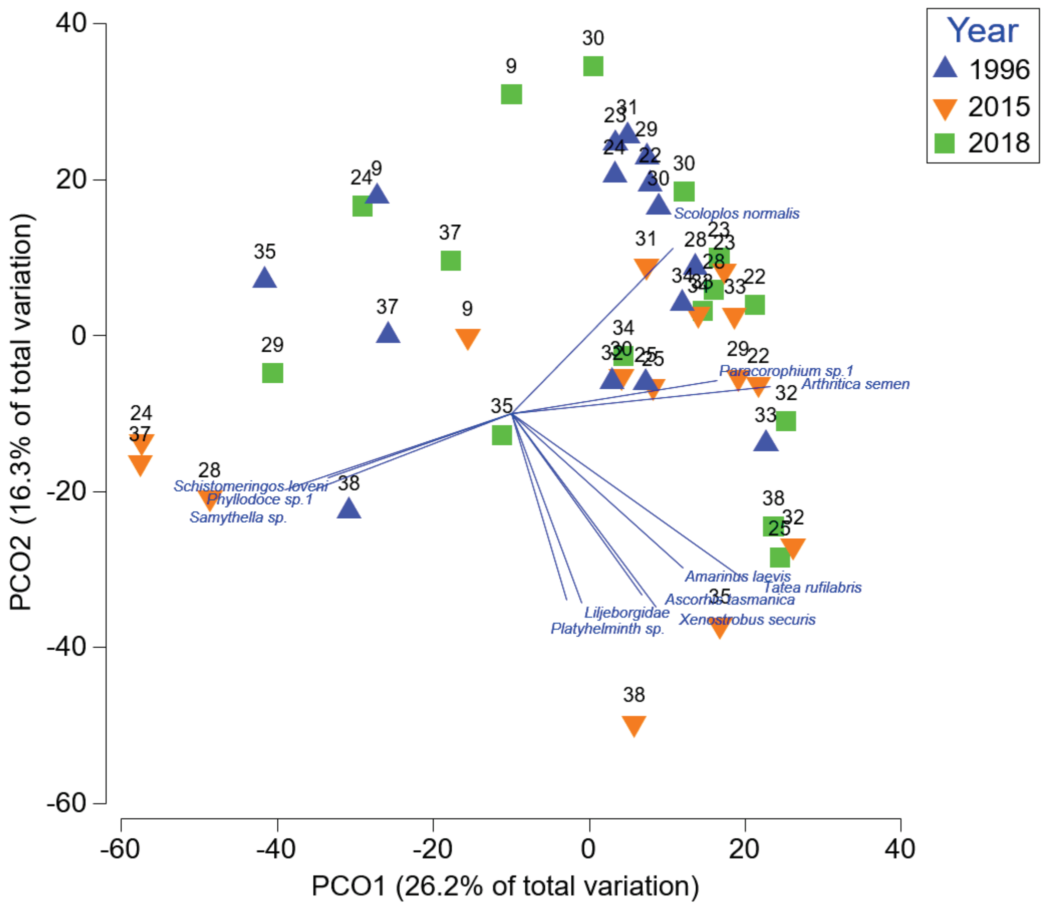


Figure 29 Principal Coordinate analysis comparing benthic communities from 1mm-sieved grab samples at WHA sites in 1996, 2015 and 2018. Species shown have a 0.6 correlation

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