Environmental Research in Macquarie Harbour

FRDC 2016/067: Understanding oxygen dynamics and the importance for benthic recovery in Macquarie Harbour

PROGRESS REPORT

Approved by the Project Steering Committee and FRDC

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EXECUTIVE SUMMARY

This report provides an ongoing update on the status of dissolved oxygen (DO) and benthic conditions in Macquarie Harbour. It follows on from the results previously outlined in the IMAS reports released through 2017 - 2019. 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. In the January 2019 report we noted that the 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. Faunal abundance and diversity was less affected as a result. This report presents the results and preliminary interpretation of a repeat survey of benthic communities in June 2019 and DO monitoring data up until November 2019.

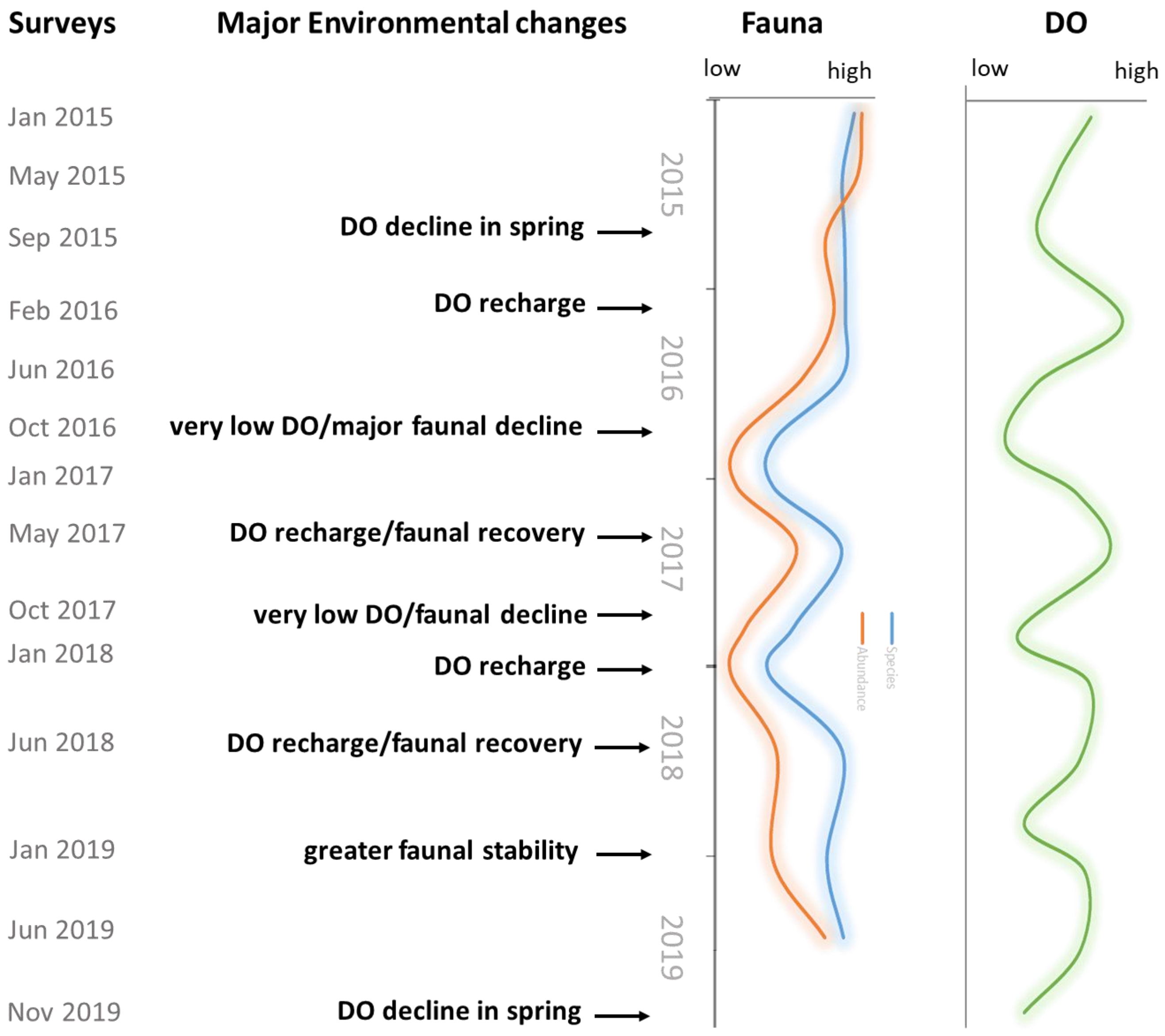
In Spring 2018 the decline in bottom water oxygen concentrations wasn't as low as observed in the previous two springs and didn't continue for as long due to a sustained period of recharge and replenishment of bottom waters that began in middle of spring 2018 and extended through to late autumn 2019. The faunal survey in January 2019 demonstrated that benthic conditions had improved relative to that observed at the same time of year in 2018 and 2017. This pattern has continued in the latest faunal survey in June 2019. Notably, at the majority of both lease and external sites faunal abundance and the number of species have returned to or are closely approaching the range observed prior to the decline in spring 2016-early 2017.

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, two more sites than in the January 2019 survey. One site had a thin mat of *Beggiatoa* in comparison to five in January 2019 and there was no streaming *Beggiatoa* recorded. At the external sites, the presence of *Beggiatoa* remains lower than observed in 2016/17, again observed at 4 of the 28 sites, and in all cases classified as patchy. In the June 2019 survey there was a decrease in the presence of dorvilleid polychaetes at both farm (88 → 59% of dives) and external sites (61→ 18% of dives) compared with January 2019 when the presence of dorvilleids had increased. There was also a reduction in the number of sites with high dorvilleid scores.

Each year since the major deterioration of benthic conditions observed in spring 2016, we have reported improved benthic conditions in the following 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 the improved benthic conditions compared with previous years is consistent with the less severe decline in DO in the preceding spring of 2018 relative to that observed in spring 2017 and 2016. These signs are certainly encouraging; however, it is important to remember that oxygen levels in the middle and bottom waters of the harbour are still lower than observed historically, and in spring 2019 oxygen levels in the bottom waters have again declined to the very low levels reported previously, coinciding with a period of higher river flows and limited oceanic recharge. The cycle observed represents a complex interplay between the many factors that influence the consumption of oxygen (e.g. organic matter and nutrient inputs) and those that drive its resupply (e.g. wind, river flow). Each year our understanding of recovery dynamics in the harbour continues to improve; the next round of faunal surveys is scheduled for early 2020.

For a timeline[1] of the major environmental events observed over the course of this study, the following schematic highlights changes in benthic faunal communities and bottom water dissolved oxygen (DO).

[1] It is important to note that there was no faunal survey in spring 2018, and as such there may well have been a decline which could not be represented in the schematic below. However, the faunal declines of the previous two springs were evident in the following January survey. In contrast, faunal abundance and species numbers in January 2019 remained high relative to the previous January surveys. Although we present oxygen data for the CSIRO mooring that highlights bottom water recharge from late December 2019, we haven't updated the timeline because we don't yet have access to data from the remaining string sites throughout the harbour; this will be updated in the next report.


Surveys
Major Environmental changes
Fauna
DO
low
high
low
high
Jan 2015
May 2015
Sep 2015
Feb 2016
Jun 2016
Oct 2016
Jan 2017
May 2017
Oct 2017
Jan 2018
Jun 2018
Jan 2019
Jun 2019
Nov 2019
DO decline in spring
DO recharge
very low DO/major faunal decline
DO recharge/faunal recovery
very low DO/faunal decline
DO recharge
DO recharge/faunal recovery
greater faunal stability
DO decline in spring
2015
2016
2017
2018
2019
Abundance
Species

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BACKGROUND

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 that 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 the harbour to support finfish aquaculture and predicting the length of fallowing required for benthic recovery in this system specifically. This also has major implications for future stocking plans in the harbour. It is clear that DO concentrations have been, and will be, a major determinant of the benthic response over the coming months and years. 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 Fisheries Research Development Corporation (FRDC) funded project FRDC 2016-067: Understanding oxygen dynamics and the importance for benthic recovery in Macquarie Harbour to address these needs. This information is essential for both operational management of farming activities and the sustainable management of the harbour over the longer term.

FRDC 2016-067 comprises three work packages that together will provide a much clearer understanding of both the effectiveness of fallowing and passive remediation for benthic recovery, and the drivers and importance of oxygen dynamics for recovery. Work package 1 (WP1) will assess 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[2] months. Work package 2 (WP2) will see the further development of the real time DO observation network in the harbour. This includes 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 WHA) and north (close to the entrance to the ocean).

The third work package (WP3) involves the 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. In early 2018 funding for this project was extended for a further two years. This includes all three work

[2] In the 2 year extension the benthic surveys will be conducted twice a year

packages described above plus the addition of a fourth work package that will see the installation of new river and tide gauges and mapping of nutrient and microbial dynamics in the harbour; information that will allow for the biogeochemical implementation of CSIRO's model to further resolve and quantify the biological and chemical contribution to oxygen dynamics in the harbour.

This report provides an update on environmental conditions in Macquarie Harbour based on the most recent benthic surveys conducted in June 2019 and water column observations up until mid-November 2019.

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).

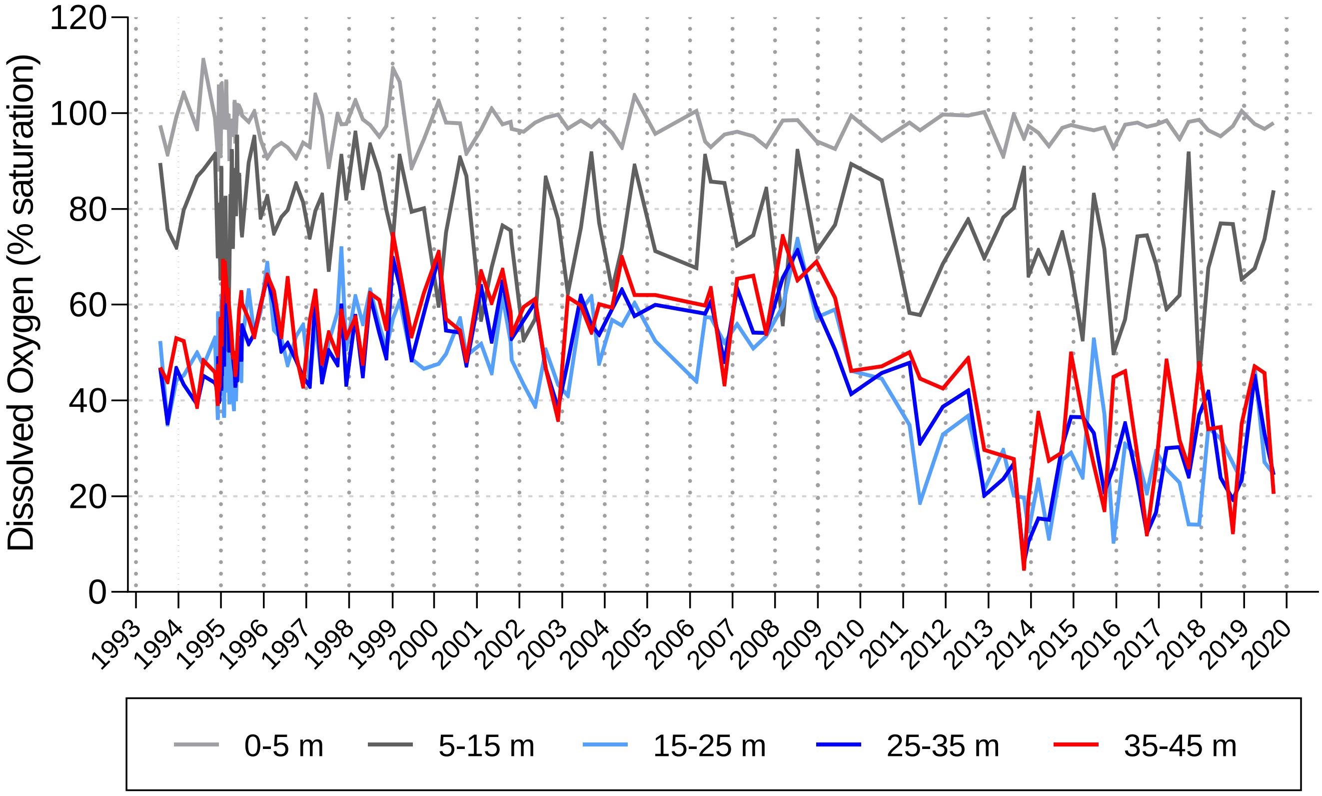

Figure 1 Long term trend in DO within a number of depth ranges at EPA site 12 (updated from MHDOWG 2014).

The contour plots produced from the three real time strings have been updated to include data up until mid-November 2019 (Figure 3-5). These figures demonstrate the cycle of recharge and replenishment of oxygen in the bottom waters through Summer and Autumn and the decline in Winter and Spring. Following the sustained period of recharge that extended from October 2018 through to May 2019, bottom water oxygen levels have again declined to the very low levels reported previously (Figure 3-5), coinciding with period of higher river flows and limited oceanic recharge. Data from the CSIRO mooring (Figure 6) highlight the deeper halocline through late spring -early summer in 2019 compared to 2018, consistent with higher rainfall on the west coast compared with the same time the previous year. 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 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.

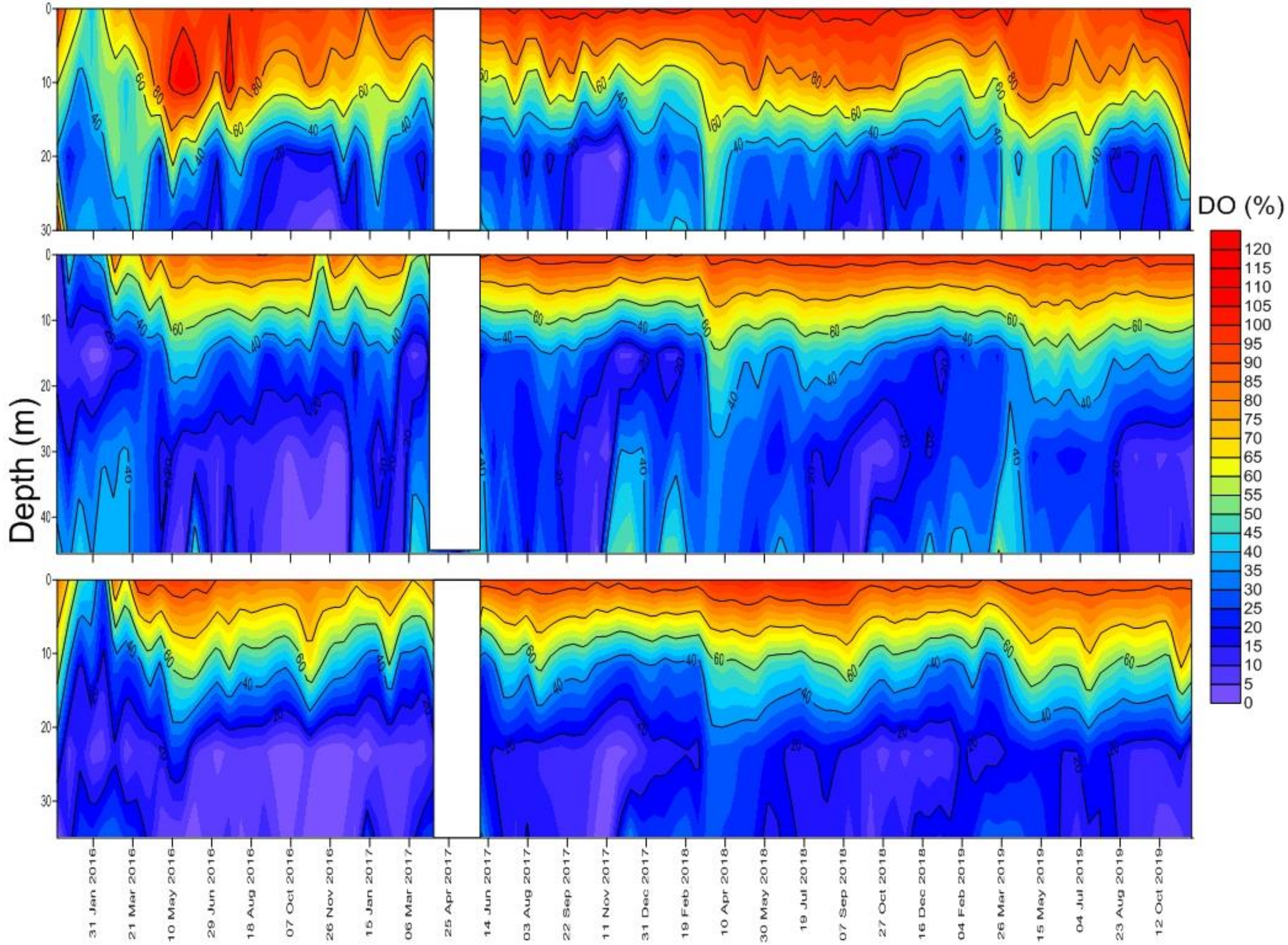

Figure 3 Contour plots showing DO profiles through the water column from the environmental strings at Table Head Central (top panel), Strahan (middle panel) and Franklin (bottom panel) over the period from December 2015 to mid-November 2019. Note, the data that underpins these plots for the period Dec 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).

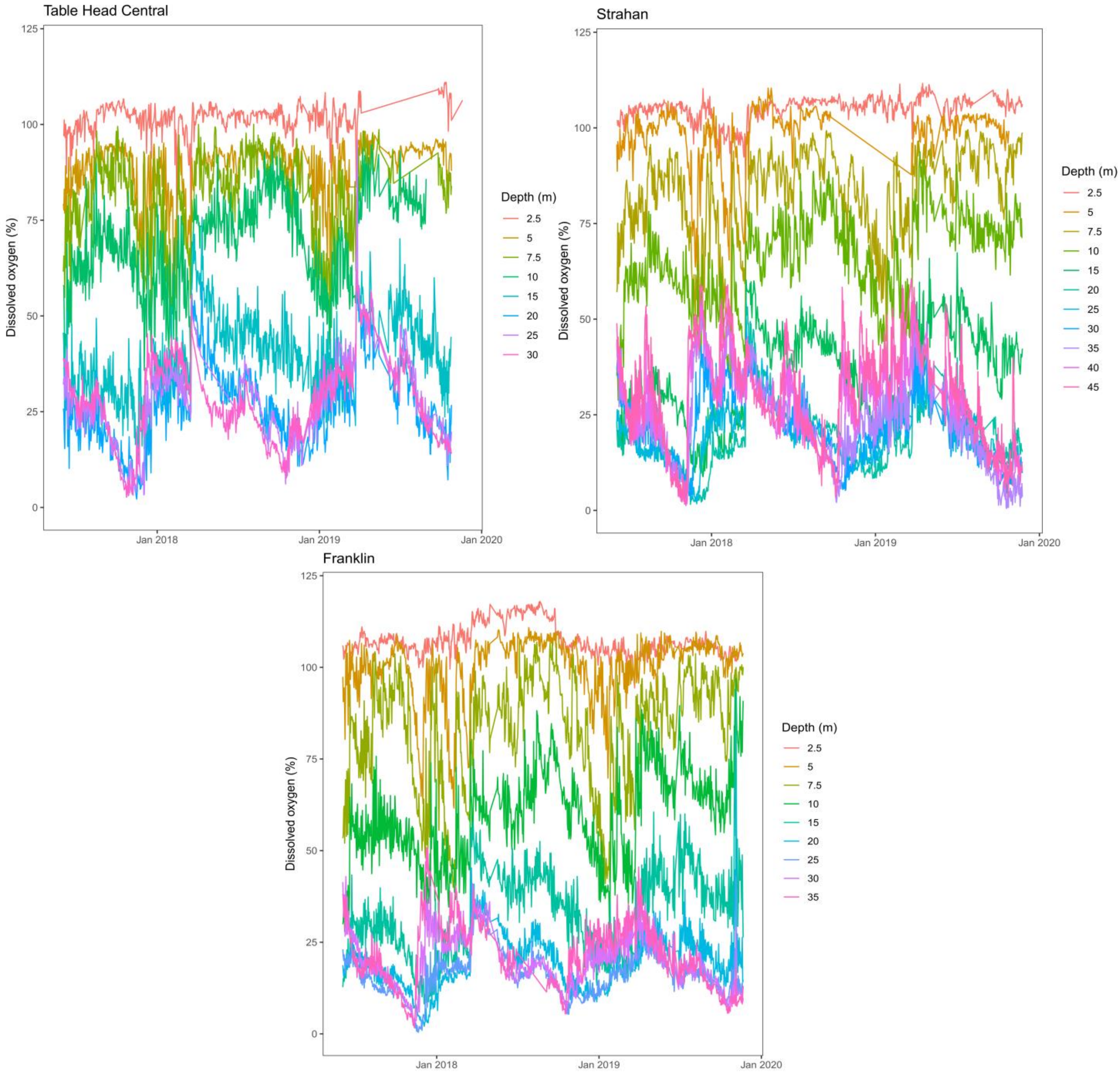

Figure 4 Daily mean DO (% saturation) levels at sensor depths from strings at Table Head Central, Strahan and Franklin over the period from the beginning of June 2017 to November 2019.

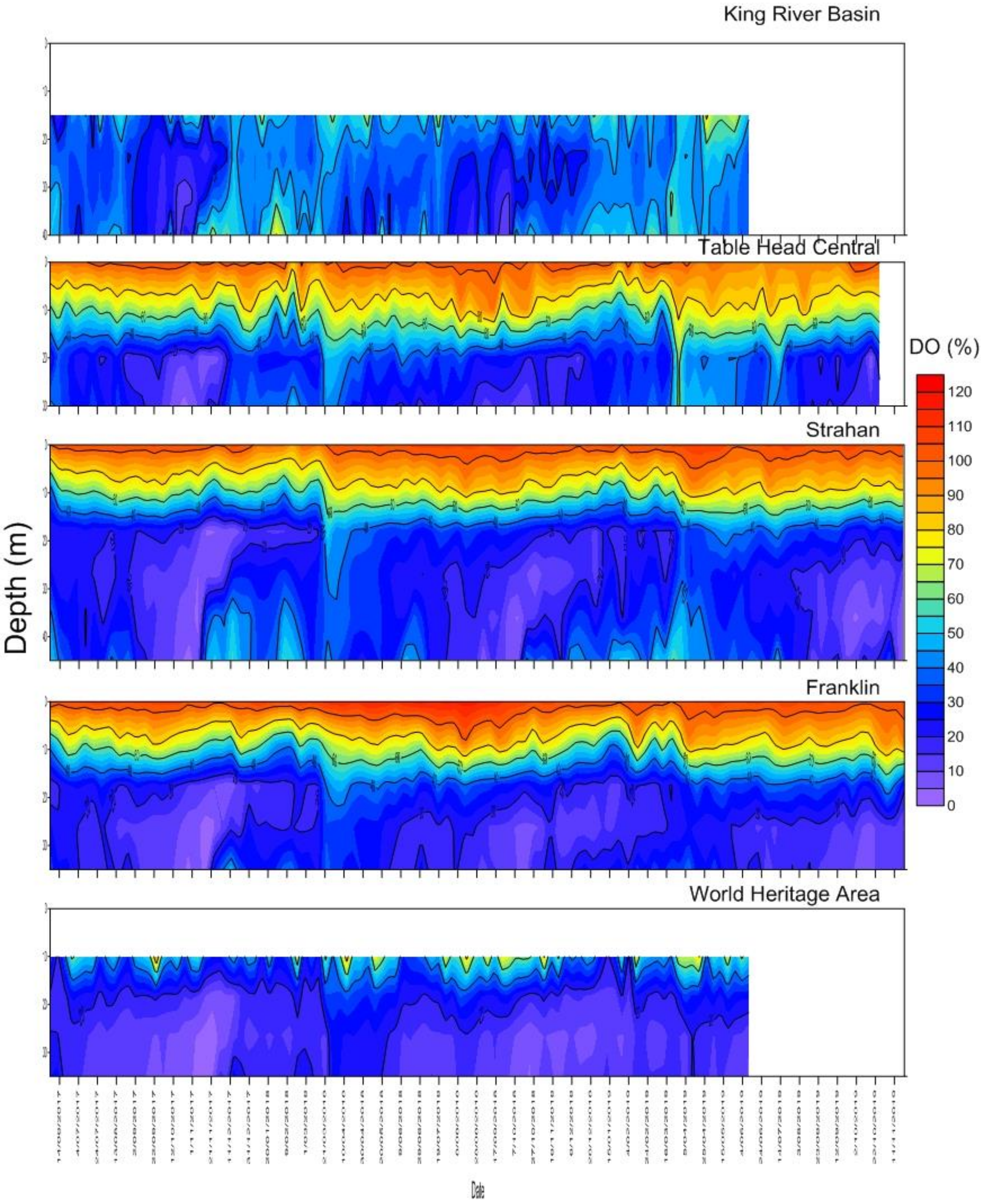

Figure 5 Contour plots showing DO profiles through the water column from the environmental strings at King River Basin, Table Head Central, Strahan, Franklin and the World Heritage Area over the period from the beginning of June 2017 to late May 2019. This represents the data from the upgrade to the 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.

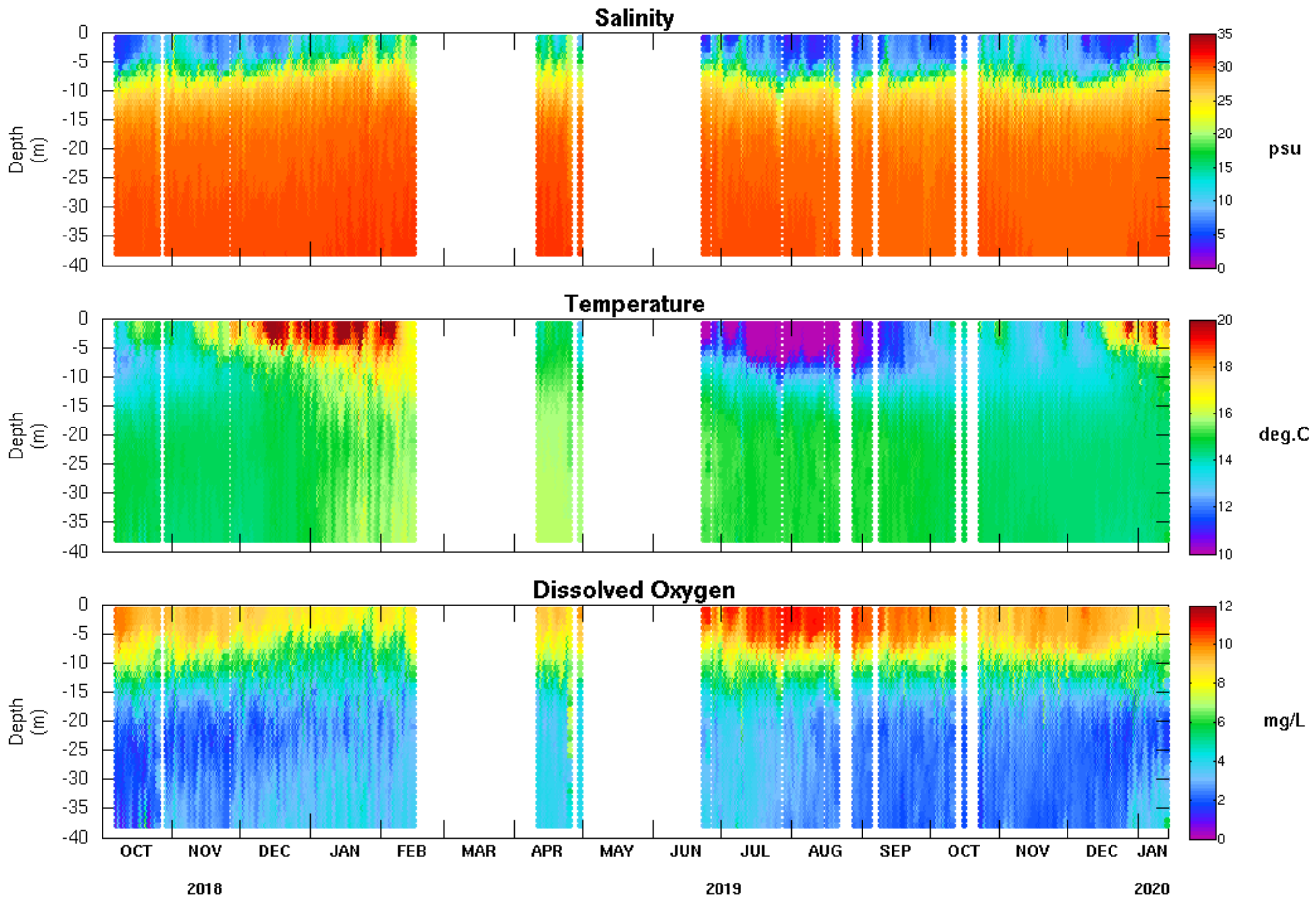

Figure 6 Observations from the CSIRO profile mooring at King River Basin site (Figure 2) showing the temporal change of water column salinity, temperature and dissolved oxygen concentration from October 2018 to January 2020. Profiling operations were suspended (i.e. the gaps in the figure) during very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

BENTHIC CONDITION

In June 2019, IMAS conducted a benthic survey of five leases and 24 external sites as part of FRDC 2016-067 (Figure 7, Table 1). This represents the 13th benthic survey conducted under consecutive FRDC projects (FRDC 2014-038, FRDC 2015-024, FRDC 2016-067) since the beginning of 2015. The work was initiated (via. FRDC 2014-038) when video footage identified an increase in abundance of dorvilleid polychaetes. In addition, it was noted that there were two dorvilleid species in the video footage and 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. 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. The major decline in the abundance and number of species of benthic fauna observed in October 2016 was the final survey of the Macquarie Harbour component of FRDC 2015-024 but it was felt that it was important to extend the research to assess benthic recovery and the effectiveness of fallowing, and as such FRDC 2016-067 was initiated. FRDC 2016-067 extended the benthic sampling to include an additional lease (lease 5) and more external sites[3].

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

Following the major decline in fauna observed in spring 2016, we observed signs of benthic faunal recovery in both abundance and number of species in autumn 2017. In spring 2017 there had been a subsequent decline in both the abundance and number of species of benthic fauna at lease sites concomitant with the return of very low DO concentrations in bottom waters throughout the harbour. In the 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 2017. In the December 2018 report we noted that 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 January 2019 survey of benthic fauna suggested that the fauna was less affected as a result. In this survey, abundance and species diversity had increased from that observed in January 2019

[3] 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.

consistent with the recovery observed in winter in previous years; however, the results vary by location.

At lease 4, the northern most of the study leases, total abundance increased at 0 m in comparison to the January 2019 survey and all previous surveys (Figure 8). At the other distances, total abundance and the number of species was similar to, or lower than observed in January 2019. Importantly, both abundance and the number of species are within the range reported historically at the lease, including prior to original decline from spring 2016-early 2017. Bottom water DO concentrations were similar to that recorded in the January 2019 survey and within the range reported for this time of year in previous surveys (Figure 8).

At lease 3, there was an increase in abundance and number of species at all distances (except 250 m which was similar) in comparison to the January 2019 survey (Figure 9). When data was pooled into 2 distance categories (i.e. those closest: 0, 50 and 100m sites pooled and more distant: 250 and 500m sites pooled), both abundance and the number of species at the sites closer to the cage are within the range reported historically at the lease, including prior to the original decline from 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 similar to that recorded in the January 2019 survey and within the range reported for this time of year in previous surveys (Figure 9).

At lease 2, abundances and species numbers were similar to or higher across all distances in comparison to the January 2019 survey (Figure 10). Importantly, both abundance and the number of species are within the range reported historically at the lease, including prior to original decline from spring 2016-early 2017. Bottom water DO concentrations were lower compared to that recorded in the January 2019 survey, but within the range reported for this time of year in previous surveys (Figure 9).

Lease 1, the most southern lease has seen a further increase in total abundance and the number of species from that observed in January 2019 (Figure 11). Since the original decline in faunal abundance and species numbers observed in spring 2016, there has been a steady recovery, notably since the January 2018 survey. Species numbers and abundance have now returned to (or are approaching) the range observed prior to the decline (Figure 11). Bottom water DO concentrations were similar to that recorded in the January 2019 survey and within the range reported for this time of year in previous surveys (Figure 11).

At lease 5, there are typically higher abundances and more species on the shallower SE transect as compared to the deeper NW transect. In the June 2018 survey the differences weren't as distinct as in previous surveys (Figure 12). This was again evident in the January 2019 survey, although both total abundance and the number of species had declined at most distances relative to that observed in June 2018. In this survey, abundances and the number of species have remained consistent with these previous surveys, however there was a decrease in abundance along the SE transect where, for the first time, abundances were generally lower than on the NW transect. Bottom water oxygen concentrations on both transects were similar to that recorded in the previous two surveys (Figure 12).

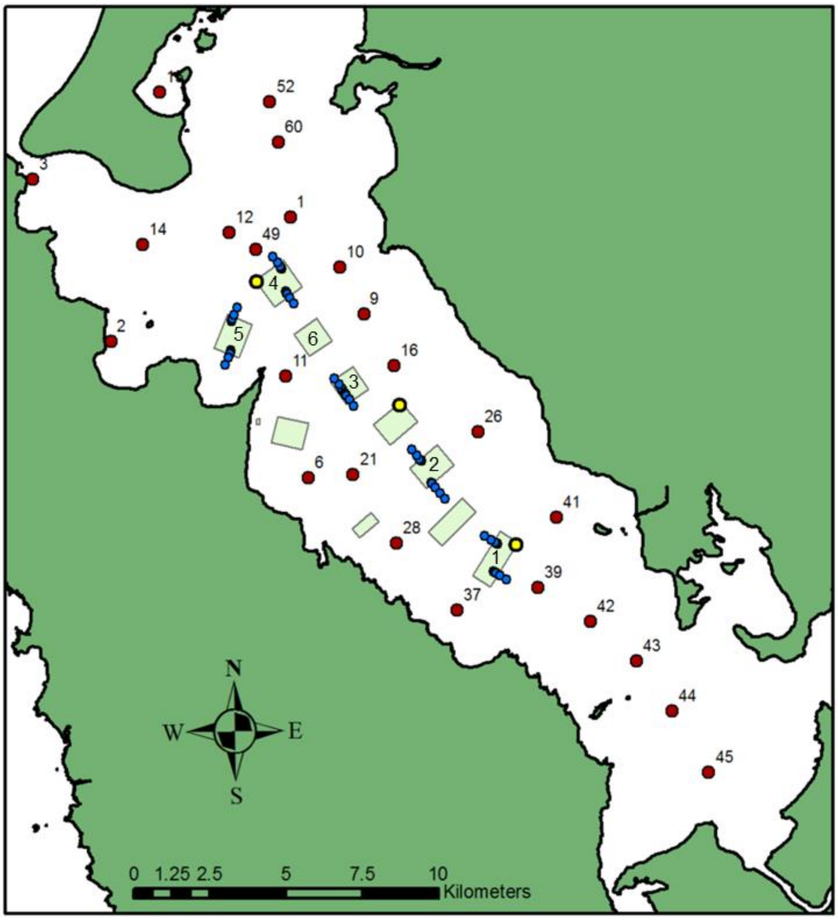

Figure 7 Maps showing external (red), lease (blue) and environmental string (yellow) sites. There are 2 transects from each of the study leases with five sites (at 0, 50, 100, 250 and 500m) on each transect.

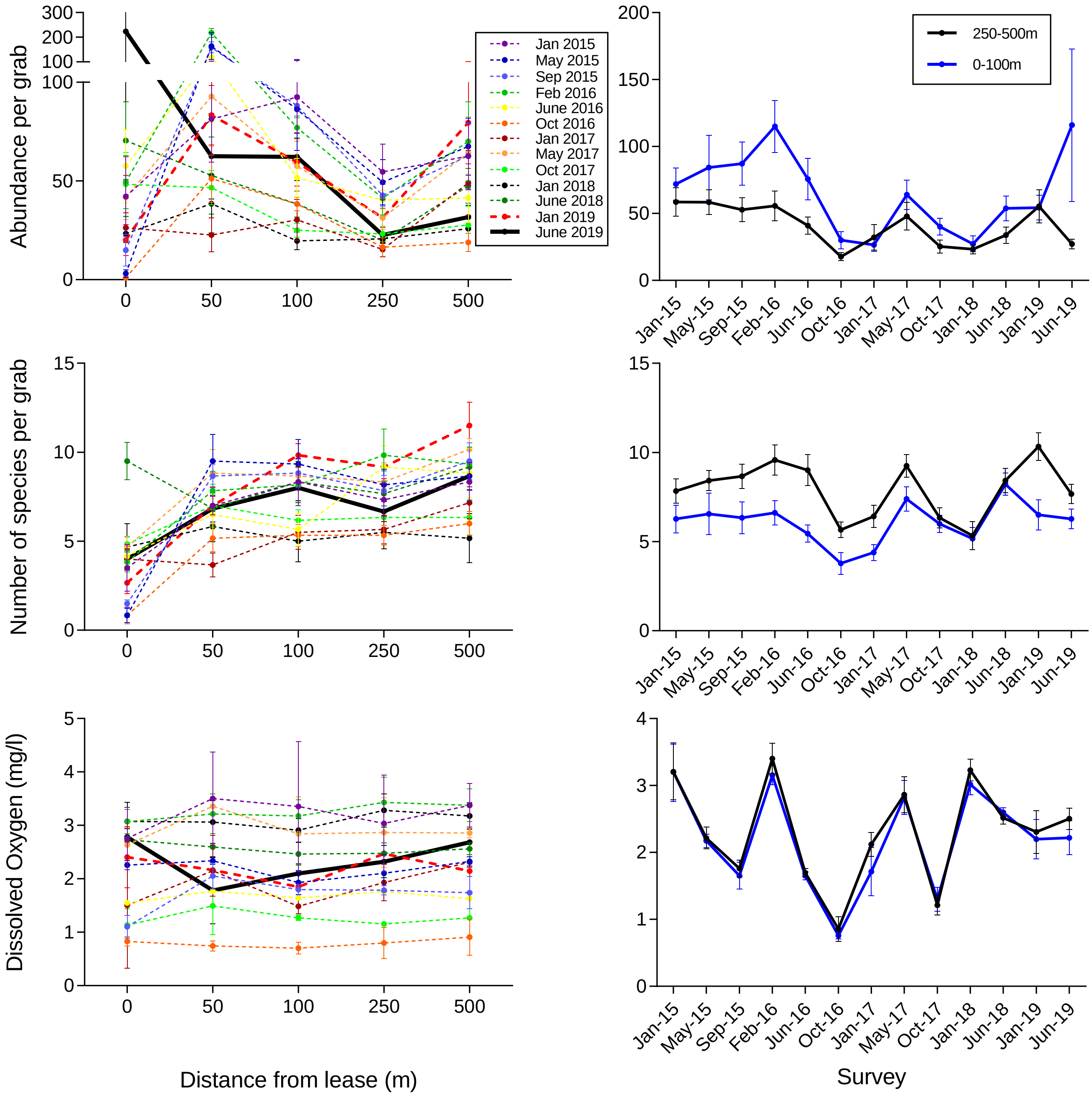

Figure 8 Lease 4 plots of total infaunal (>1mm) abundance (per grab = ~ 0.0675m²; top panel), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (bottom panel) in relation to 1 (left panels): distance from the cage (0, 50, 100, 250 and 500m from 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 (June 2019) has been highlighted with a thick solid black line.

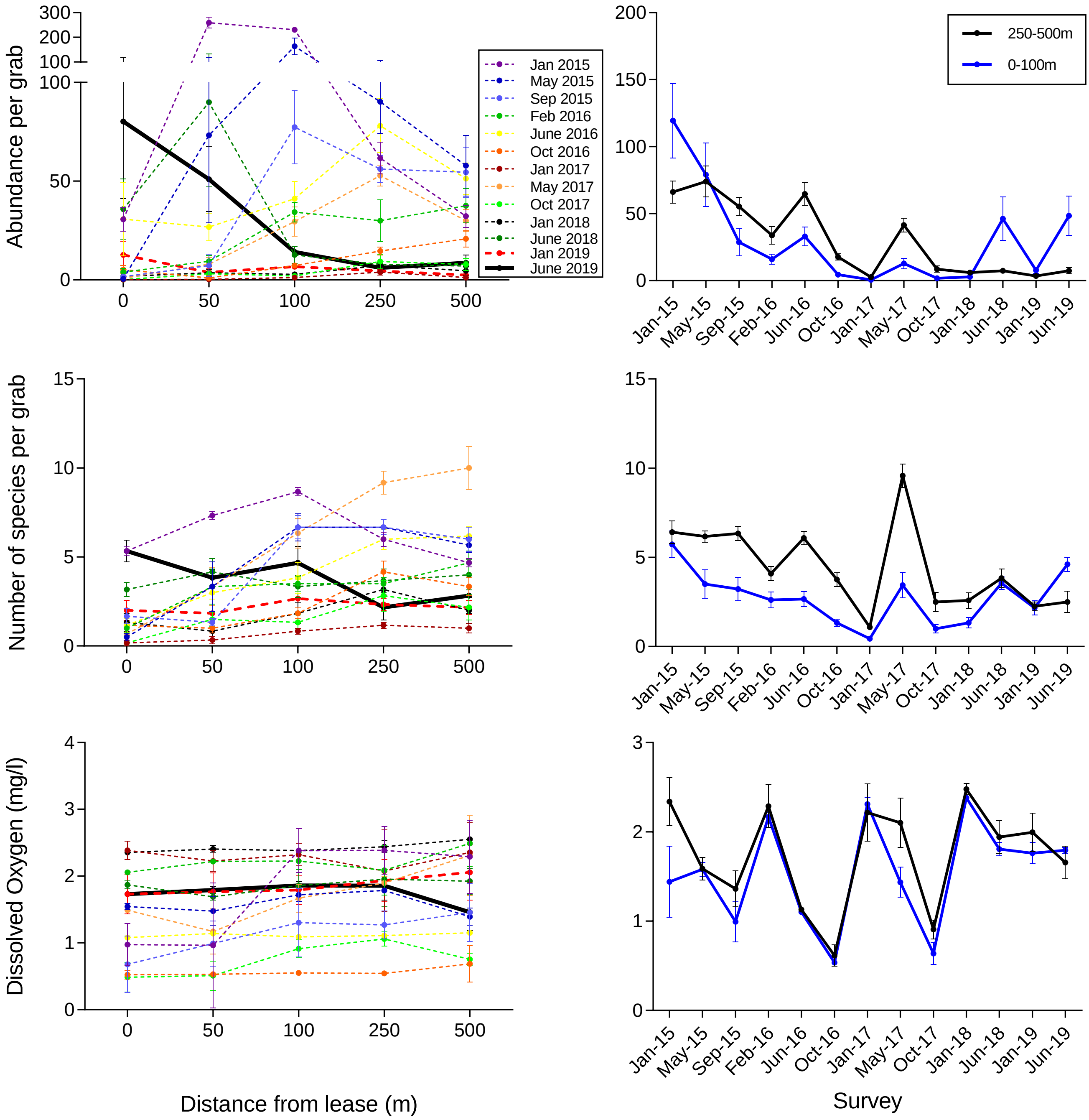

Figure 9 Lease 3 plots of total infaunal (>1mm) abundance (per grab = ~ 0.0675m²; top panel), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (bottom panel) in relation to 1 (left panels): distance from the cage (0, 50, 100, 250 and 500m from 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 (June 2019) has been highlighted with a thick solid black line.

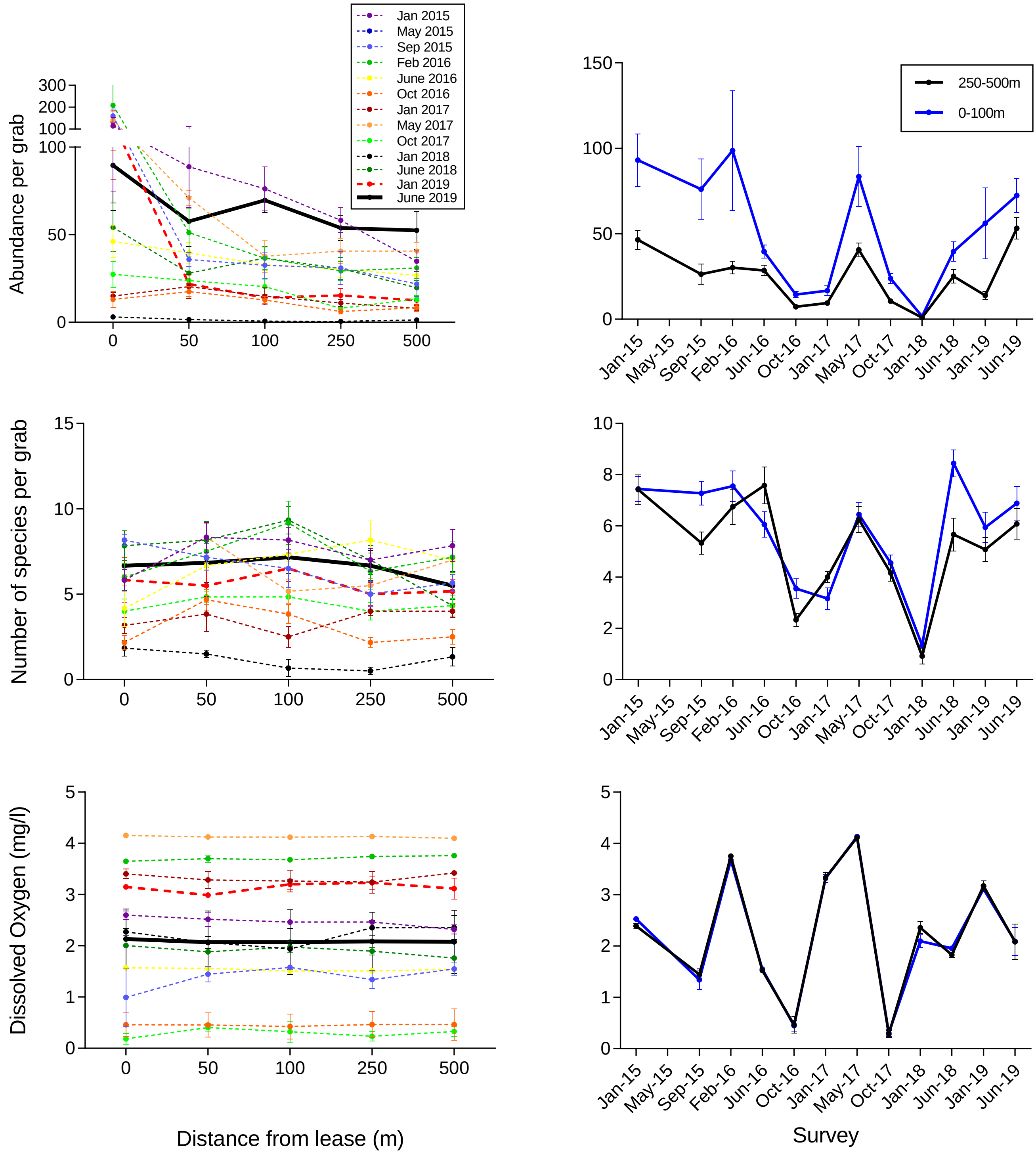

Figure 10 Lease 2 plots of total infaunal (>1mm) abundance (per grab = ~ 0.0675m²; top panel), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (bottom panel) in relation to 1 (left panels): distance from the cage (0, 50, 100, 250 and 500m 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 (June 2019) has been highlighted with a thick solid black line. Note, lease 2 was not surveyed in May 2015.

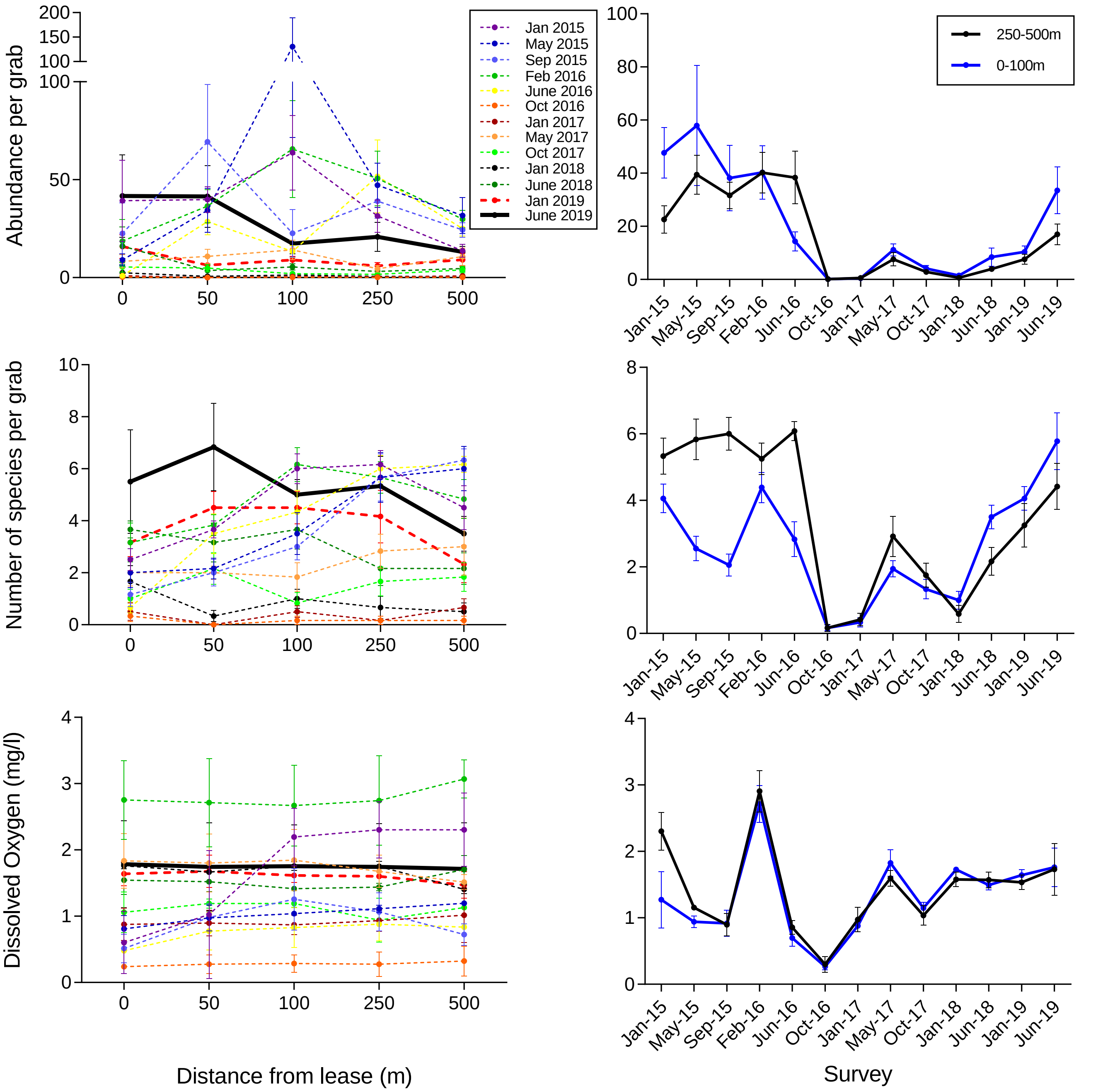

Figure 11 Lease 1 plots of total infaunal (>1mm) abundance (per grab = ~ 0.0675m^2; top panel), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (bottom panel) in relation to 1 (left panels): distance from the cage (0, 50, 100, 250 and 500m 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 (June 2019) has been highlighted with a thick solid black line.

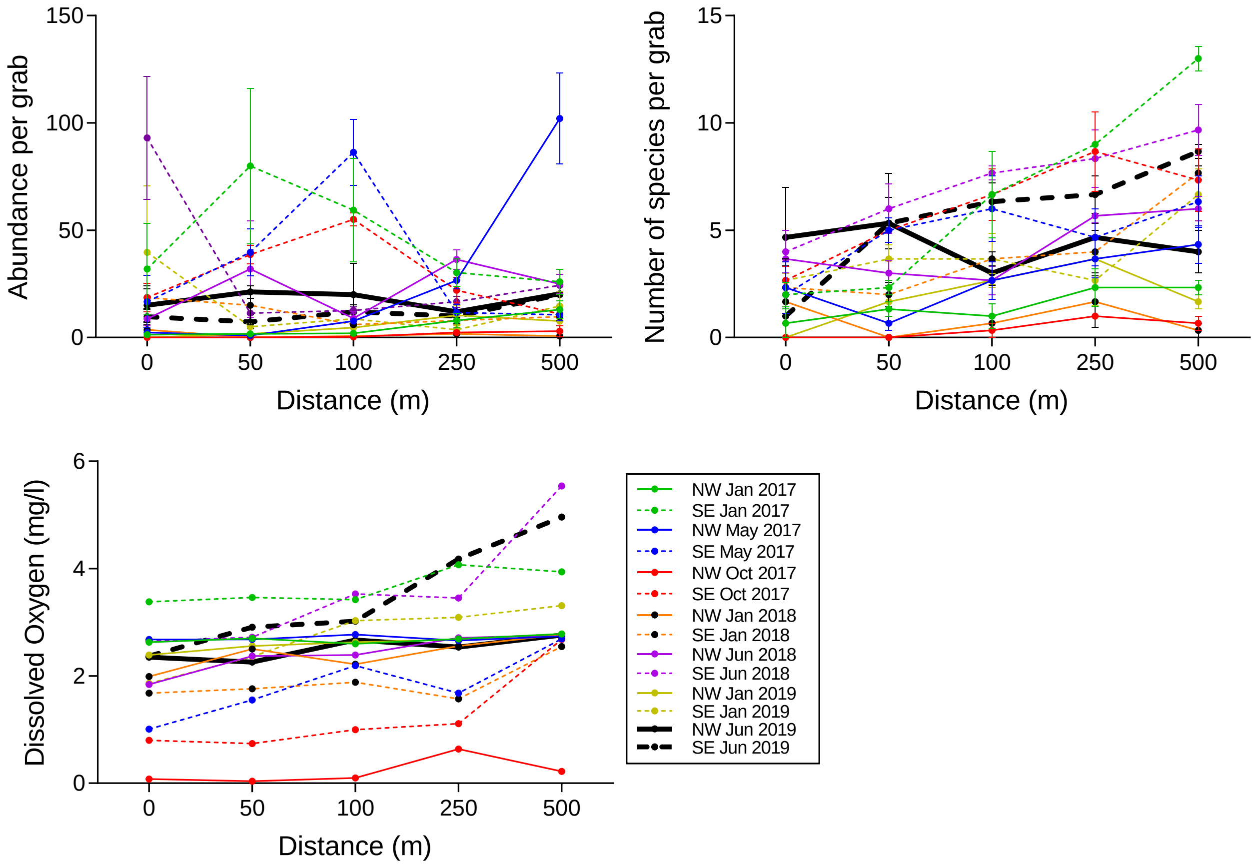

Figure 12 Plots of total infaunal (>1mm) abundance (per grab = ~ 0.0675m²), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (at 0, 50, 100, 250 and 500m from cages at lease 5 during the January 2017 – June 2019 surveys. The data shows the 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 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. 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 the 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 October 2016 was in the deeper central region of the harbour (Figure 14).

Faunal abundance and species numbers at the majority of the external sites in the June 2019 survey was within the range recorded in our surveys prior to the decline in spring 2016 – early 2017, however there were some exceptions. At the four southernmost external sites (39, 42, 43 and 44) where abundances have been the slowest to recover from the original decline in spring 2016 – early 2017, abundances increased at these sites in the January 2019 survey and continued to do so in this survey (Figure 14). Faunal abundance and the number of species at these four sites are now well within the range reported previous to the decline; and in some cases (abundance at sites 39 and 43 and species number at site 39) are higher than that recorded in the first two surveys conducted in January 2015 and February 2016.

At the other end of the Harbour, there was a decline in abundance and number of species at the sites to the north in closer proximity to the entrance to the ocean (i.e. sites 2, 3, 12 and 14). The cause for this decline is difficult to explain given the proximity to well oxygenated waters; however, it may reflect variation or the difficulty in sampling that occurs using a grab sampler in the hard sand substrates found at these sites. The next survey in early 2020 will provide greater certainty as to whether there has been a shift in faunal abundance and species numbers at these sites.

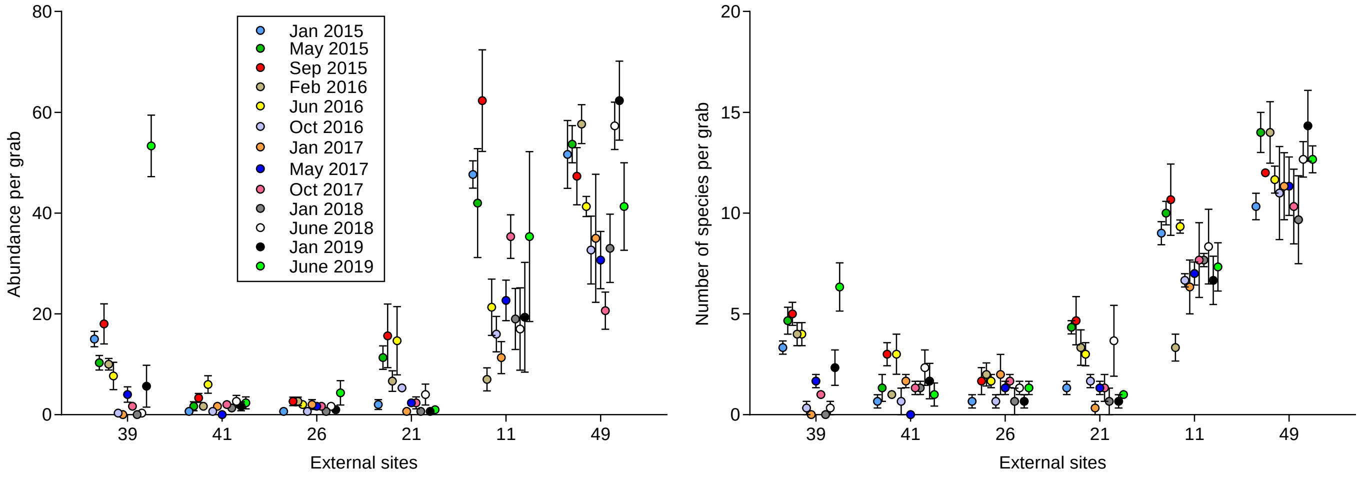

Figure 13 Plots of total infaunal (>1mm) abundance (per grab = ~0.0675m²) and number of species collected in grabs (n=3) at 7 external sites in Macquarie Harbour from surveys between January 2015 and June 2019. The data for each site represents the mean (±SE) from three replicate grabs. Note that site 26 was not surveyed in May 2015.

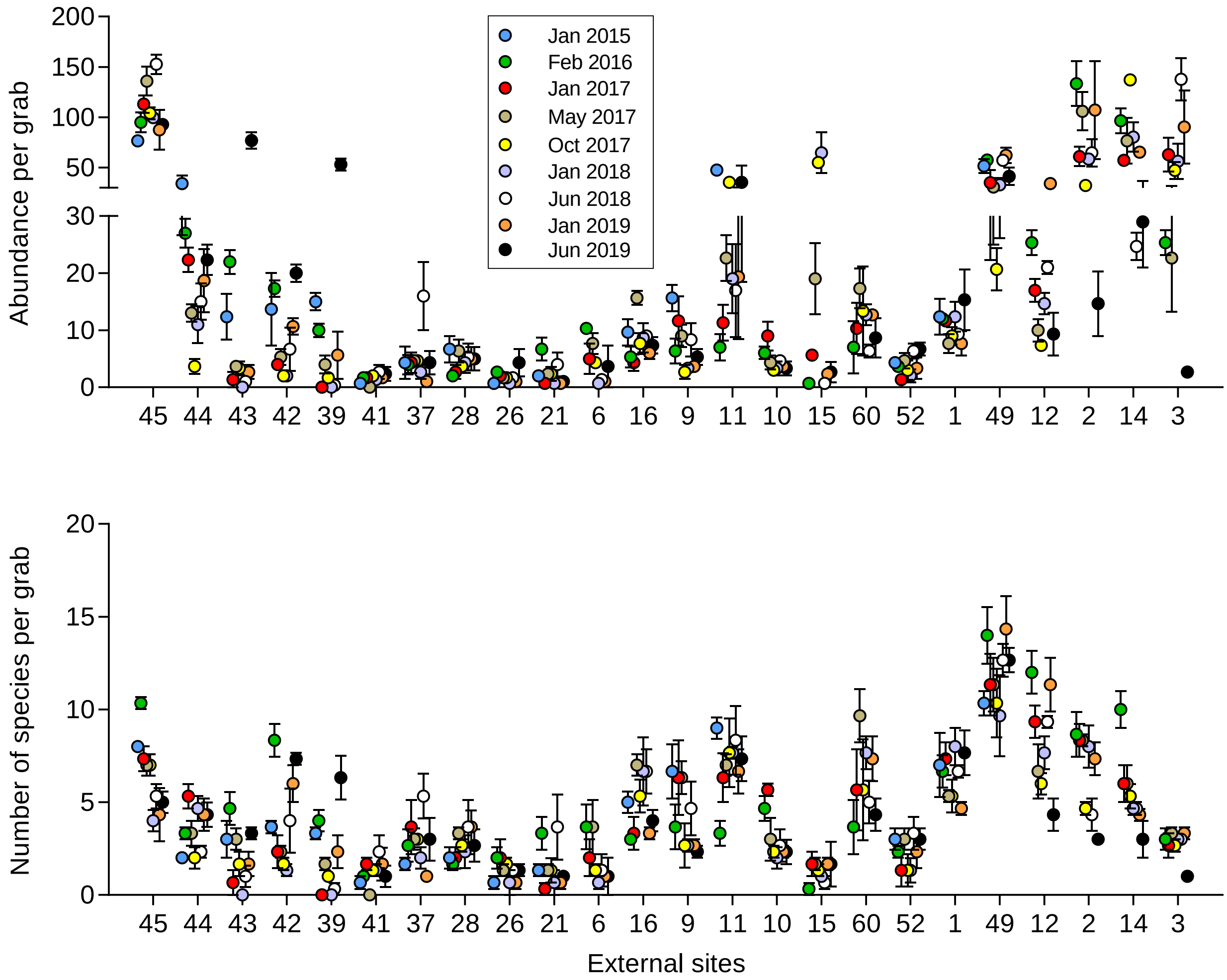

Figure 14 Plots of total infaunal (>1mm) abundance (per grab = ~0.0675m²) and number of species collected in grabs (n=3; bottom panel) at 23 external sites in Macquarie Harbour from surveys in January 2015, February 2016, January 2017 and May 2017, October2017, January 2018, June 2018, January 2019 and June 2019. 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[4]. 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 spring 2018, a video assessment of all sites was completed in September 2018. The results of this survey have been included 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, January 2019 and June 2019 video surveys demonstrated that the presence of *Beggiatoa* remains low relative to that observed in the October 2016 and January 2017 surveys (Table 4). In the June 2019 survey, *Beggiatoa* was observed on more of the lease dives (15 of 51) than January 2019 (13 of 51) but there was only one instance of a lease dive recording a thin mat of *Beggiatoa*. In January 2019 there were five observations of thin mats and one observation of streaming *Beggiatoa*. In June 2019, there was also one observation of a thin mat of *Beggiatoa* and no streaming *Beggiatoa*. When present, *Beggiatoa* cover was categorised as patchy or thick patchy. Most of these occurrences were on lease 5 where patchy *Beggiatoa* was scored at all distances along the NW (except for 250 m where no *Beggiatoa* was found) and SE transects. At the external sites, *Beggiatoa* was observed at 4 of the 28 sites in the September 2018, January 2019 and June 2019 surveys, with all cases being categorised as patchy/thick patchy (Table 4, Figure 15).

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). 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 59% 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

[4] 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.

category (i.e. 0-30 dorvilleids in a dive). There was also a major decrease in dorvilleids at the external sites; with dorvilleids 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).

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 6 and 3 of 79 ROV dives in January 2019 and June 2019 respectively. 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%		

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%	36%	12%	8%		
	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	56%	17%	6%	6%	11%	6%
	Lease	42	36%	31%	14%	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%	14%	14%	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%	27%	16%	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%

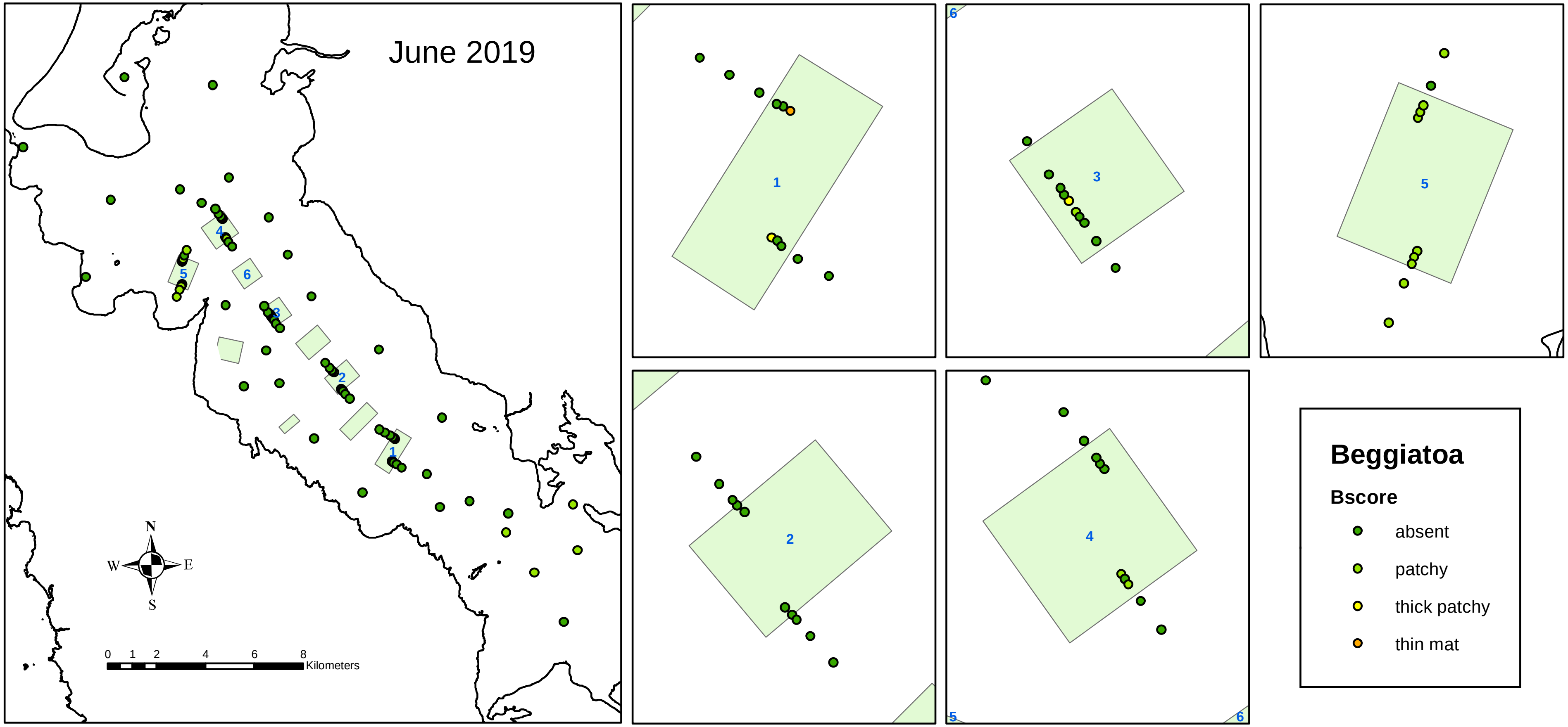

Figure 15 *Beggiatoa* score (severity) from ROV footage at study sites across the harbour on the left panel and shown in more detail for each of the study leases in the panels on the right.

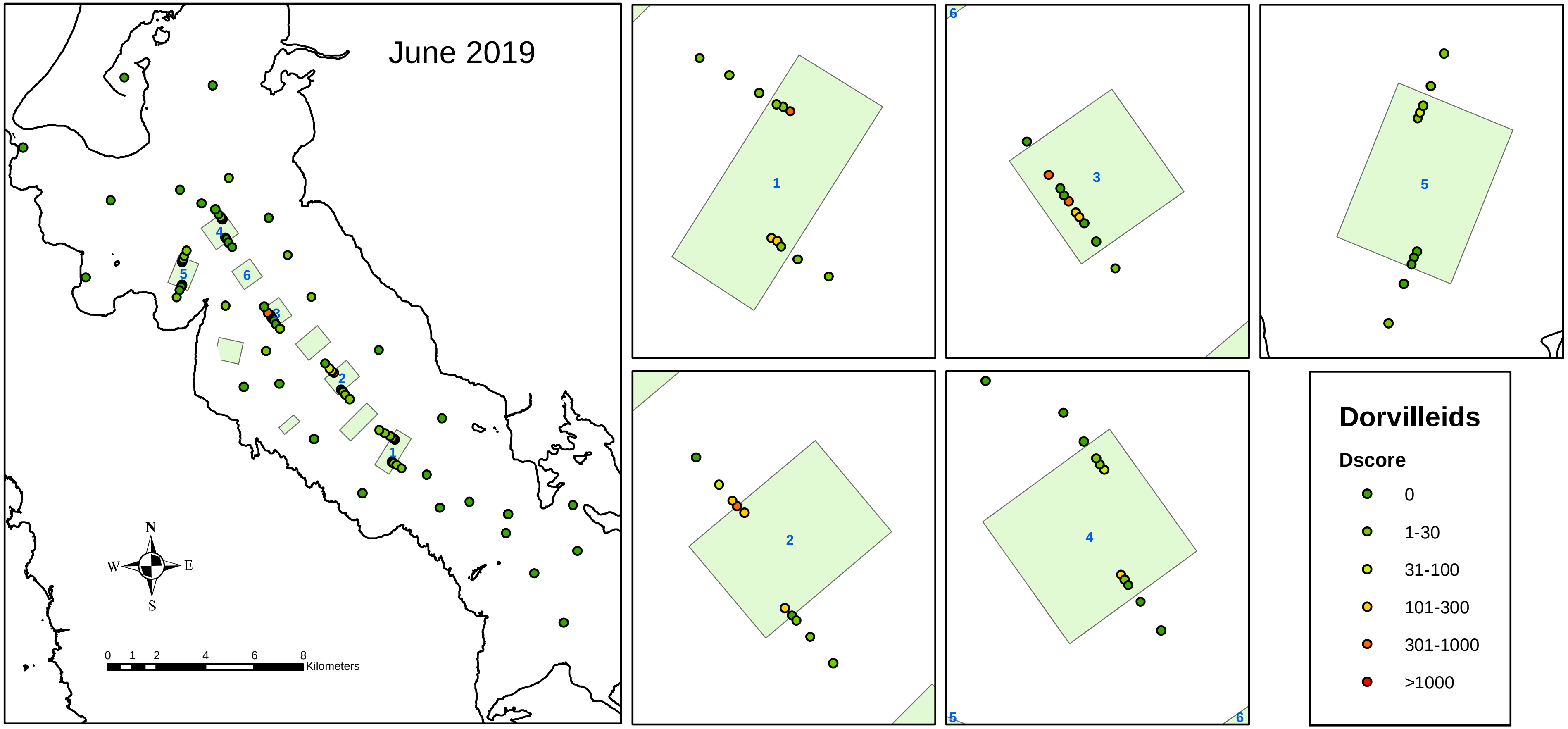

Figure 16 *Dorvilleid* score based on counts from ROV footage at study sites across the harbour on the left panel and shown in more detail for each of the study leases in the panels on the right.

REFERENCES

Andrewartha, J. and Wild-Allen (2017) CSIRO Macquarie Harbour Hydrodynamic and Oxygen Tracer Modelling. Progress report to FRDC 2016/067 Project Steering Committee.

Cresswell G.R., Edwards R.J. and Barker B.A. (1989) Macquarie Harbour Tasmania, Seasonal Oceanographic Surveys in 1985, Papers and Proceedings of the Royal Society of Tasmania, Vol. 123.

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

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, J. and MacLeod, C (2017a) Environmental Research in Macquarie Harbour – Interim Synopsis of Benthic and Water Column Conditions. Institute for Marine and Antarctic Studies (IMAS), University of Tasmania, Australia, Report to EPA and DPIPWE

Ross, J. and MacLeod, C (2017b) Environmental Research in Macquarie Harbour – FRDC 2016/067: Understanding oxygen dynamics and the importance for benthic recovery in Macquarie Harbour. Institute for Marine and Antarctic Studies (IMAS), University of Tasmania, Australia. Progress Report to the Project Steering Committee and FRDC.

Ross, J., Wild-Allen, K. Andrewartha, J. and MacLeod, C (2018) Environmental Research in Macquarie Harbour – FRDC 2016/067: Understanding oxygen dynamics and the importance for benthic recovery in Macquarie Harbour. Institute for Marine and Antarctic Studies (IMAS), University of Tasmania, Australia. Progress Report to the Project Steering Committee and FRDC.