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First large-scale ecological impact study of desalination outfall reveals trade-offs in effects of hypersalinity and hydrodynamics

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ABSTRACT

Desalination is an increasingly common method of meeting potable water demands, but the associated ecological risks are not well understood. Seawater desalination plants discharge large volumes of hypersaline brine directly into the ocean, raising concerns about potential impacts to marine life. In order to reduce impacts of brine, newer desalination outfalls are often fitted with high-pressure diffusers that discharge brine at high velocity into the water column, increasing the mixing and dilution of brine with ocean water. However, there are few published studies of marine impacts of desalination brine, and no well replicated before-after designs. Here we report a six-year study testing for impacts and subsequent recovery of sessile marine invertebrate recruitment near a desalination outfall with high-pressure diffusers. We used a Multiple Before-After-Control-Impact (MBACI) design to test for impacts and recovery at two distances (30 m and 100 m) from a 250 ML/day plant outfall, as well as a gradient design to test the strength of impacts relative to distance from the outfall. The diffusers achieved the target of less than 1 psμ salinity difference to surrounding ambient waters within 100 m of the discharge outfall, but sessile invertebrates were nonetheless impacted. Polychaetes, bryozoans and sponges reduced in cover as far as 100 m from the outfall, while barnacles showed the opposite pattern and were more abundant near the discharging outfall. Ecological impacts were disproportionate to the relatively minor change in salinity (~1 psμ), suggesting a mechanism other than salinity. We propose that impacts were primarily driven by changes in hydrodynamics caused by the diffusers, such as higher near-bed flow away from the outfall. This is consistent with flow preferences of various taxonomic groups, which differ due to differences in settlement and feeding abilities. High-pressure diffusers designed to reduce impacts of hypersalinity may inadvertently cause impacts through hydrodynamics, leading to a trade-off in minimizing combined salinity and hydrodynamic stress. This study provides the first before-after test of ecological impacts of desalination brine on sessile marine communities, and rare insight into mechanisms behind impacts of a growing form of human disturbance.

1. Introduction

The desalination industry has grown rapidly, with global capacity increasing by 57% between 2008 and 2013 (IDA, 2013). Approximately 1% of the world's population now depends on desalinated water for daily use, supplied by almost 20,000 desalination plants that produce over 90 million cubic meters of water per day (GWI, 2017). Moreover, increasingly frequent and severe climate and population driven water shortages are projected to accelerate growth in desalination in the coming years (Gude, 2016). By 2025, over 2.8 billion people across 48 countries are likely to experience water scarcity, and desalination is expected to become an increasingly critical water source for many coastal populations (GWI, 2017).

The process of seawater desalination removes salt from seawater to obtain freshwater, then typically returns a hypersaline brine to the ocean. The salinity of brine produced by the plant in the current study is approximately 65 psμ, almost double the salinity of

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ambient seawater. Due its higher density compared to seawater, brine creates a plume around the outfall and sinks to the seabed unless mixed with ocean water. Hypersalinity can damage or be lethal to marine organisms by interfering with osmotic processes (Rachid and Chouikhi, 2005), particularly in combination with other stressors, such as temperature and metals (McLusky et al., 1986). If currents are low, brine can form a persistent layer on the seabed and create a press disturbance to benthic marine communities. Other potential effects of brine on water quality include changes in temperature and dissolved oxygen, although these are generally only issues for thermal plants (Lattemann and Höpner, 2008). Brines can also contain toxic contaminants, such as metals, anti-scalants, coagulants and coagulant aids, antifoaming agents and cleaning chemicals (Roberts et al., 2010), which can accumulate in sediments around outfalls (Muhammad, 2002; Romeril, 1977) or in marine organism tissues (Lin et al., 2011). Additionally, brine can lower pH, which can negatively impact calcifying marine organisms (Fabricius et al., 2013). There are therefore multiple pathways by which brine can impact the marine environment, including changes in salinity, temperature, water quality, hydrology, and pollution with contaminants (Roberts et al., 2010).

Concurrent to growth in the number and size of desalination plants has been a transition from thermal to reverse osmosis (RO) treatment processes, with over 95% of production now achieved by RO plants (GWI, 2017). Although RO plants reduce the problem of heated effluent, they produce far greater volumes of brine than thermal plants (Peñate and García-Rodríguez, 2012). Water recovery rates from RO plants are between 35 and 55%, dramatically increasing the rate of brine discharged to the ocean per day (Greenlee et al., 2009). Potential impacts of brine on marine ecosystems have and will continue to rise rapidly, but knowledge of these impacts is severely limited (Missimer and Maliva, 2017). In 2010, a literature review found no studies of impacts of desalination plants on marine life that used before-after designs and had well-replicated reference sites (Roberts et al., 2010). Several years later, despite enormous growth in the industry, there are still no such published studies. There is, therefore, urgent need for more comprehensive studies of ecological impacts of desalination plants in the scientific literature.

In recent years, engineers have achieved their environmental targets for salinity and other brine constituents by using high-pressure diffusers, which enhance the rate of mixing with ocean water (Christodoulou et al., 2014). Unlike typical wastewater plumes that are positively buoyant and rise to the surface (e.g. sewage), a brine plume is dense and will sink towards the seabed where there are less ongoing mixing processes. Better mixing of the jet and plume with ocean water increases dilution, thereby reducing ecological disturbances of hypersalinity (Miller et al., 2007a). The amount of near-field dilution will depend primarily on the receiving water currents, the discharge velocity, and angle of discharge (Chin, 1987). Fig. 1A illustrates the mixing jet, the falling plume, and the baroclinic spreading of the plume as the last of the buoyancy is dispersed. The mixing jet is dominated by momentum of the discharged brine, while the falling plume is dominated by the negative buoyancy, and the baroclinic spreading is influenced by both density differences and ambient currents (Miller et al., 2007b). The dilution of the brine plume is achieved by entraining seawater; however, this does result in additional volumes of water being transported from the mid and upper parts of the water column to near the bed.

The aim of this study was to assess the ecological impacts of a desalination outfall on sessile marine invertebrate recruitment, and their potential recovery once operation ceased. The desalination plant produced approximately 250 ML of freshwater per day, and modelling predicted that the high-pressure diffusers would dilute the brine to <1 psμ above background salinity within 100 m of the outfall. The plant shut down after operating for approximately two years due to fulfilment of local water requirements, giving opportunity for tests for ecological recovery. Marine invertebrates are ideal test species due to their sensitivity to water quality, and inability to escape a disturbance once settled. We used a MBACI (Multiple Before-After-Control-Impact) design (Keough and Mapstone, 1995) sampling twice per year for six years, at multiple test and reference locations. We tested for impacts at two distances from the outfall (30 m and 100 m, with four reference locations), and for a gradient in impacts with distance from the outfall. Additionally, we continued sampling for one year after plant shutdown to test for long-term effects on recruitment. This study provides the most rigorous test of the ecological effects of desalination brine to date, and new insight into the mechanism of impact.

2. Materials and methods

2.1. Sampling design

Sessile invertebrate recruitment sampling was based on an MBACI (multiple Before-After-Control-Impact) design. We tested for impacts at two distances from the outfall (30 and 100 m) aligned with the direction of the north-south longshore current, which we refer to as ‘near’ and ‘far’ outfall locations (Fig. 1C). Four reference locations were positioned between 1.5 and 5 km north and south of the outfall (Fig. 1C). Each location consisted of two sites that were 20 m apart. There were four panels at each site, and two settlement plates attached to each panel.

Sampling times were divided into three periods that we refer to as *before* (prior to plant operation), *discharging* (while the plant was operational), and *shutdown* (following plant shutdown). Within each period there were three to five sampling rounds, with rounds occurring biannually (Fig. S1). Tests for impacts were achieved by comparing samples in the before period to the discharging period, and tests for recovery compared both the before and discharging periods to the shutdown period.

2.2. Recruitment plates and deployment

Sites were situated on high-energy open coast near Kurnell, NSW, Australia (Fig. 2). The seabed was predominantly rocky-reef at depths between 21 and 28 m. At each site, we deployed an array of four PVC backing panels (each 30 × 30 cm), connected by heavy chain and anchored by several 40 kg weights. Panels were spaced approximately 1.5 m apart, and arrays were tethered to a mooring line which stretched between sites within a location. Attached to the underside of each backing panel were two 11 × 11 × 0.5 cm black Perspex settlement plates, the sampling units to collect marine invertebrate communities. Settlement plates faced downwards towards the reef, and their surfaces were roughened to facilitate recruitment. Recruitment depends on several factors including material, substrate, depth and orientation, so there may be differences between recruitment onto settlement plates vs. natural rocky reef (Anderson and Underwood, 1994). However, settlement plates control for and standardise the above factors, and have been used as a sampling tool for hard substrate marine communities for decades (Clark and Johnston, 2005, 2009; Keough, 1984).

To ensure that recruitment panels had been deployed appropriately, a remotely operated vehicle (ROV) was used by inspect the plates at each site in each round. Dates of panel deployment and collection in each sampling round are shown graphically in Fig. S1. An additional round of sampling was conducted between sampling rounds 3 and 4, but weather-induced bias in the panel collection

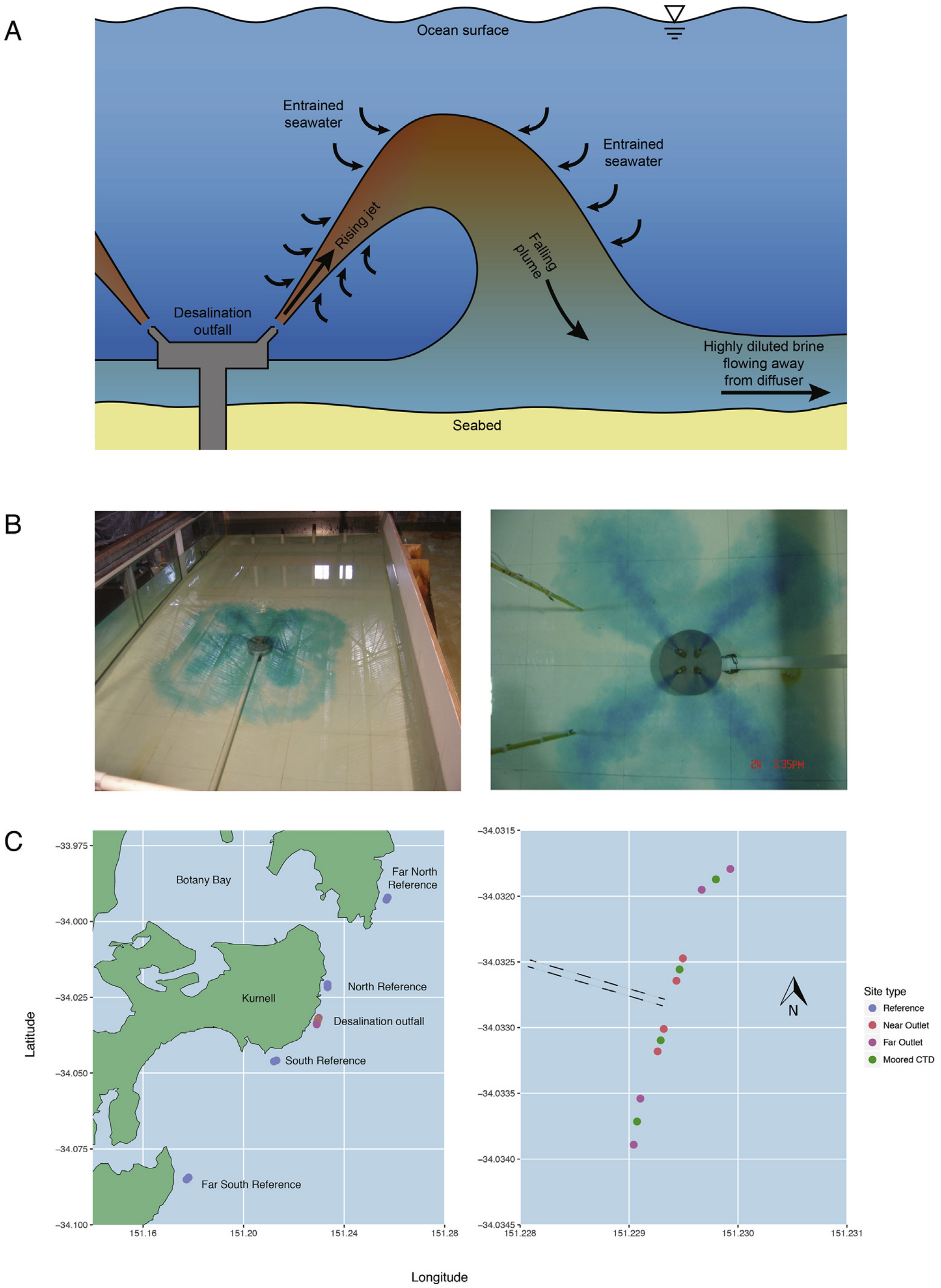

Fig. 1. Brine plume characteristics and sampling sites. (A) Schematic illustration of the features of the brine plume. (B) Photographs of scale model of an outfall diffuser, with brine visible as blue dye. (C) Map of sampling sites, showing positions of reference and outfall locations along NSW coast (left panel), and outfall locations at smaller scale (right panel). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

date meant that the round was excluded from analyses.

2.3. Collection of recruitment plates

Recruitment panels were retrieved after approximately 12–14 weeks of deployment, depending on weather conditions. They were transported to the laboratory in seawater, photographed within 24 h of collection, then stored in flowing seawater aquaria for census. Each community was sampled live under a dissecting microscope. Sampling was limited to the inner 10 × 10 cm section of the plate, excluding the area around the bolt head (approximately 4 cm^2) which was typically damaged during plate collection. The proportion cover of each taxon was recorded by counting its occurrence under 49 regularly spaced points (7 × 7 grid) superimposed over a plate. Taxa that occurred on a plate but were not recorded under a point were given nominal cover of 0.5%. Each taxon was photographed, and voucher specimens were preserved in 80% ethanol.

2.4. Statistical analyses of impacts and recovery

MBACI analyses were used to test for impacts at distances of 30

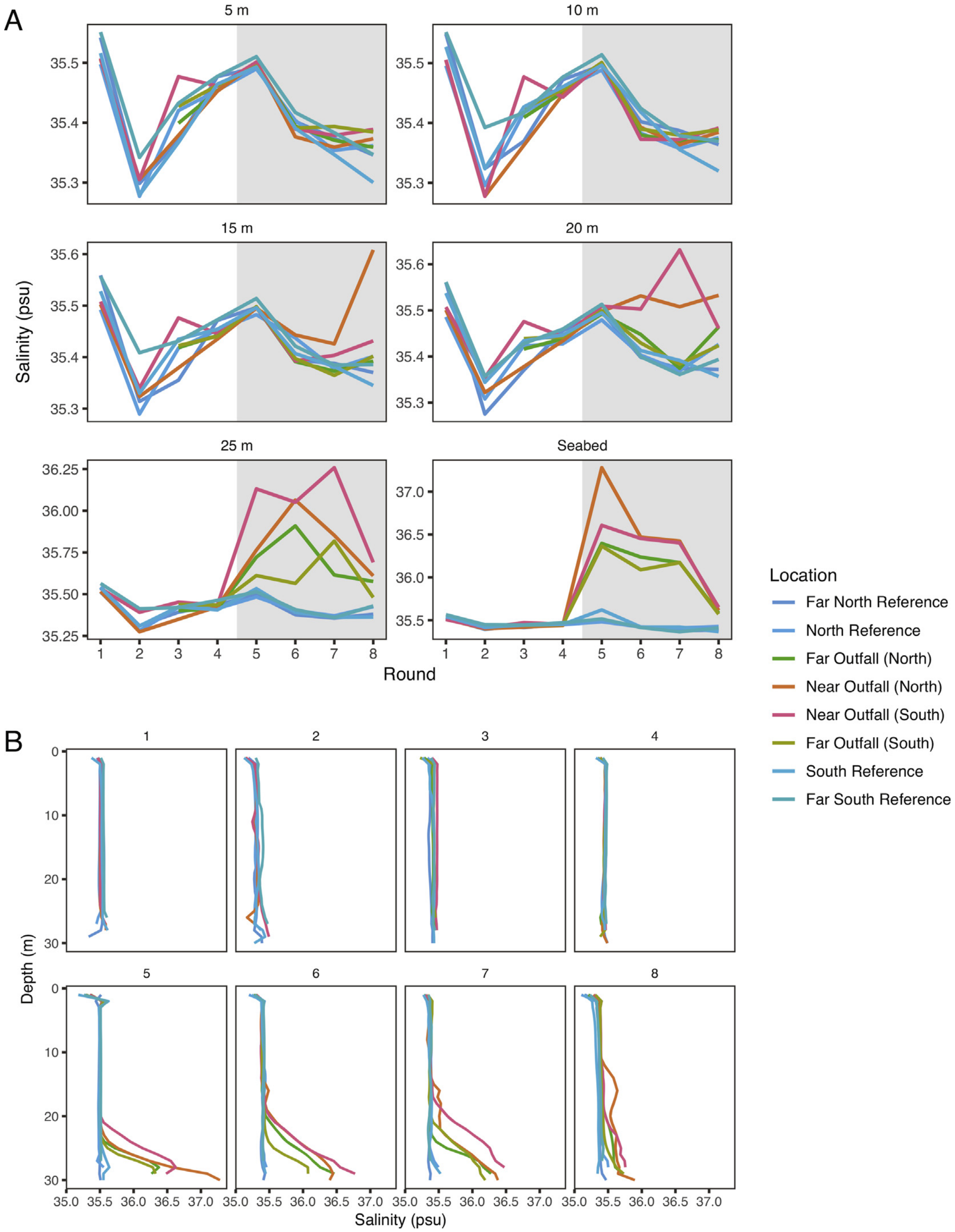

Fig. 2. Salinity in the 'before' and 'discharging' periods. (A) Mean salinity at each location in each round, at 5 m depth intervals and at the seabed. Shaded region indicates the time when the plant was operational (the discharging period). (B) Salinity depth profiles for locations in each round. The plant was operational in the lower row of panels (rounds 5–8) only.

m and 100 m from the outfall (referred to as near and far outfall locations, respectively), and recovery from any impacts detected (Keough and Mapstone, 1995). The aim of an MBACI is to detect temporal change at outfall locations, relative to change at reference locations. The period × test interaction is the statistical term of most interest, as it indicates whether change between two time periods differed between outfall and reference locations. Comparison of before vs discharging periods provides a test for impacts of the outfall, while comparison of before and discharging periods vs the shutdown provides a test for recovery from impacts. Note that we use the term recovery to describe an absence of impacts, rather than return to an original state. This is because recruitment changes naturally through time at all locations, so communities in the shutdown period may differ from the before period due to natural temporal variation.

Permutational Multivariate Analysis of Variance (PERMANOVA) was used to test for significant change in community structure at outfall locations (Anderson, 2001). Fixed effects were period (before vs during) and test (outfall vs reference), and random effects were round (nested in period) and location (nested in test).

Canonical Analysis of Principal Coordinates (CAP) was used to visualize the multivariate structure of data and to identify taxa that contributed most to differences (Anderson and Willis, 2003). This routine is similar to Principal Coordinate Analysis (PCO), but rotates the ordination to maximize differences between levels of a factor of interest, in this case the period × test interaction. Prior to analysis, multivariate data were square-root transformed to reduce the influence of abundant taxa. Similarity matrices used the distance measure of Bray-Curtis dissimilarity.

As univariate response variables, we analysed community-level metrics (e.g. species richness, Shannon-Weiner diversity, proportion bare space), proportion cover of major taxonomic groups, and proportion cover of the 20 species that occurred at the most sampling sites and rounds. Inference for univariate response variables was based on generalized linear mixed models (Bolker et al., 2009), hereafter GLMM. These models are suitable for non-normal data and unbalanced designs, and incorporate random effects to account for spatial and temporal autocorrelation between samples. Period and test were fixed effects; round, location, site and panel were random effects. For proportion cover data we assumed a binomial distribution with logit-link variance, and for diversity metrics we assumed either Gaussian or Poisson distributions. Parameters were estimated with Laplace approximations (Breslow and Clayton, 1993), and P-values were obtained with Wald tests. We used the 'lme4' package (Bates et al., 2014; Bolker et al., 2009) in R v.3.3.2 (R Core Team, 2017).

For response variables that were impacted at near outfall locations, we conducted additional analyses to test for a gradient in the strength of impact with distance from outfall. This was done using GLMM with fixed factors of direction, distance, and their interaction, and random factors of round and site. For each response variable, we first tested whether the direction by distance interaction was significant ($P < 0.05$). If non-significant, the interaction was removed, and the model re-fitted with main effects of distance and direction only. If the effect of direction was non-significant, it was also removed from the model, leaving distance as the only fixed factor.

We used two approaches to test for evidence that impacted taxa 'recovered' during the shutdown period. First, we conducted an MBACI to test for an interaction between period (before vs. shutdown) and test (outfall vs. reference), and non-significant ($P > 0.25$) interaction was interpreted to infer recovery. Second, we conducted an MBACI to test for an interaction between period (discharging vs. shutdown) and test (outfall vs reference). If both (a) the interaction was significant ($P < 0.05$), and (b) the mean value in the before period was closer to that in the shutdown period than the discharging period, this was interpreted to infer recovery.

2.5. Predation exclusion experiment

There was notable fish congregation around the outfalls in the discharging period (Kelaher et al., in prep), which may have affected the cover of sessile invertebrates if they were preyed upon by fish (Bolton et al., 2017). We therefore conducted a caging experiment to test for effects of fish predation near the outfall. Caging experiments have a long history of use in experimental marine ecology for determining effects of mobile species on sessile communities (Kennelly, 1991). During the last sampling round of the discharging period, we deployed half-cage and fully-caged settlement plates at each site, in addition to the regular uncaged settlement plates. The hypothesis was that if fish predation was driving impacts, communities on caged plates should be more different from those on uncaged plates at sites closer to the outfall. The predation exclusion experiment was analysed with PERMANOVA with fixed factors of caging, test, and their interaction, and random factor of location. Planned contracts nested within caging compared each of the caging types to the uncaged treatment. Univariate patterns were inspected graphically, but not analysed since trends were visually apparent.

2.6. Salinity and temperature sampling

Salinity depth profiles were taken in the before and discharging periods, using a Seacat Profiler and a Sea-bird SBE19 conductivity-temperature-depth meter (CTD). Salinity was recorded as probes descended to the seafloor. Within each round and site, two replicate salinity measurements were taken at four sampling dates. Measurements were averaged to obtain a single value for each 1-m interval per round/site. To measure finer scale temporal variation in salinity, moored CTD units were deployed at outfall locations in rounds when the plant was operational. At each outfall location, one CTD was moored midway between the two sites where recruitment panels were deployed (Fig. 1C). These were Falmouth NXIC-CTD-BIO-AUTO or Seabird SBE37SM CTDs. Routine maintenance and service, including chlorine disinfection and screen replacement, was conducted prior to deployment and twice during deployment. Temperature at each site was recorded during the discharging period by moored CTDs at outfall locations, and Tidbits attached to recruitment panels at all locations.

3. Results

3.1. Changes in salinity and temperature

Salinity during plant operation was most elevated near the seabed, where it reached 37 psμ or 1 psμ above background salinity (Fig. 2). The average increase in salinity at the seabed was approximately 1 psμ at the near (30 m) outfall location, and 0.8 psμ at the far (100 m) outfall location. A diffuser fault caused an additional increase in salinity north of the outfall when plant operation first commenced (Round 5), but after the fault was rectified, salinity was similar in both north and south directions. Increased salinity was detected as shallow as 15 m, indicating the area to where brine was first discharged before mixing with surrounding seawater. Continuous monitoring near the outfall showed that salinity was relatively constant in rounds 5 to 7 (discharging period), with few anomalies greater than 1 psμ from the mean (Fig. S2). Fluctuations in round 8 reflect periods of intermittent plant shutdown (Fig. S2). Neither moored CTD or Tidbits showed increased temperature at outfall locations during the discharging period, relative to reference locations (Figs S3 and S4).

3.2. Community-level impacts and recovery

Despite the success of the diffusers in achieving high dilution rates and returning salinity to within 1 psμ of background at 100 m from the outfall, there were clear impacts on community structure at both outfall locations (Fig. 3). Impacts were strongest at 30 m but were still significant at 100 m (Fig. 3, Tables S1 and S2). CAP ordinations showed that impacted communities were characterised by increased cover of the barnacle *Megabalanus coccopoma* and bivalves, and reduced cover of polychaetes, bryozoans and sponges (Fig. 3). There were no significant impacts of brine discharging on species richness, Shannon-Wiener diversity, evenness, or bare space (a proxy for resource availability), at either near or far outfall locations (Fig. S5, Tables S3 and S4).

According to multivariate tests, after one year of plant shutdown communities were not statistically different from their pre-operational state, and CAP ordinations showed little difference between test and reference locations in the shutdown period

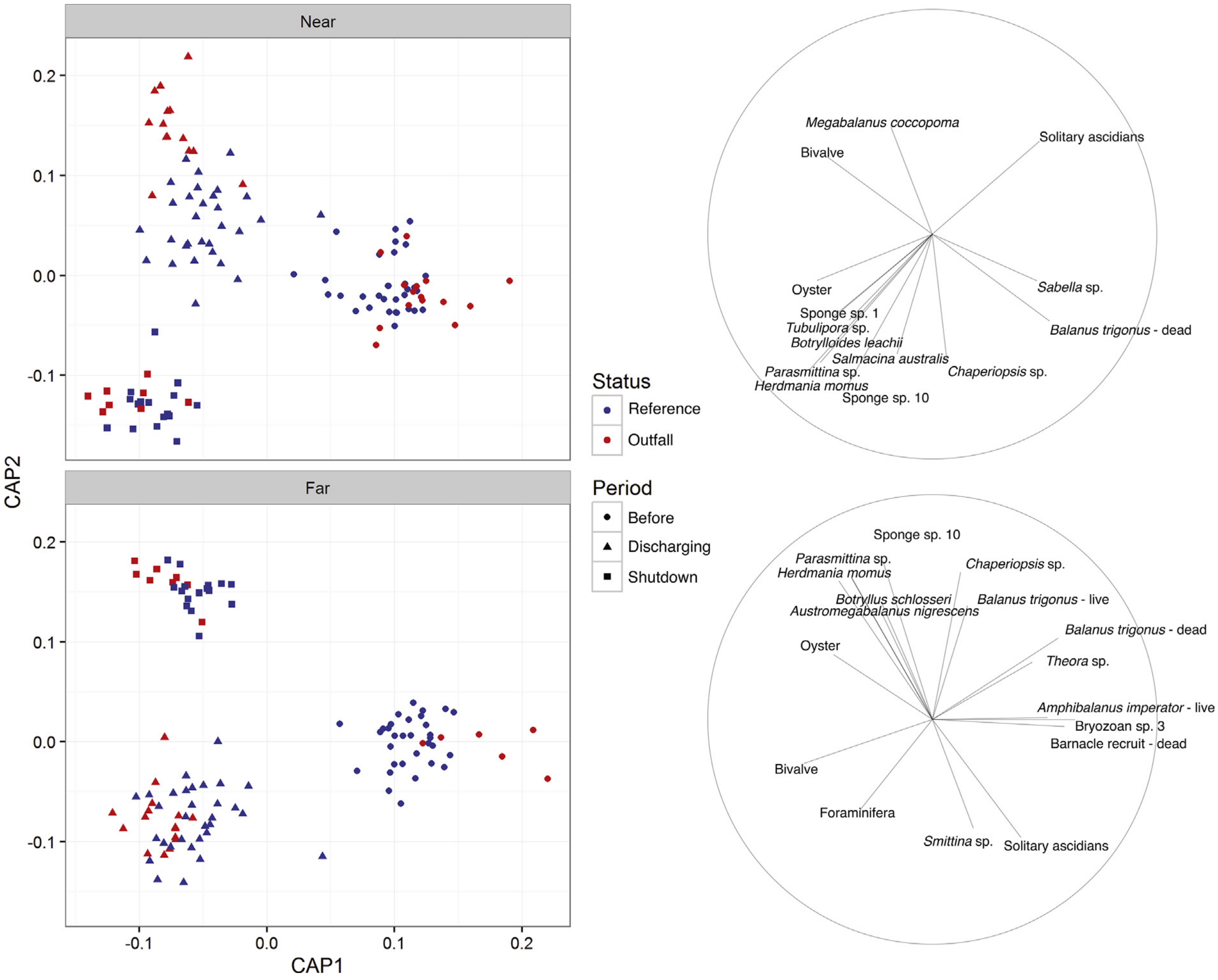

Fig. 3. Canonical Analysis of Principal Coordinates (CAP) ordination showing multivariate differences in recruitment communities, before, during, and following plant operation, at outfall and reference locations. Points represent sites within locations and rounds. Adjacent vectors indicate Pearson correlations (>0.5) between taxa and CAP axes. The circle is a correlation of 1.

(Fig. 3). The test for impact was not significant between before and shutdown periods, but was significant between discharging and shutdown periods. Both these patterns suggest that impacts to communities had ceased.

3.3. Major taxonomic groups

Several major taxonomic groups responded strongly to outfall operation. The strongest negative impact was for polychaete tubeworms, which decreased in cover at both near and far outfall locations while the plant was discharging. The effect was most prominent in the first months of the discharging period, when polychaetes were almost absent at near outfall locations. On average, polychaete cover reduced by approximately 60% at near outfall locations while brine was being discharged, and effects were weaker but still significant at far outfall locations (Figs. 4 and 5 and S6, Table S5 and S6). Both bryozoan and sponge cover were negatively impacted at the near outfall location, but impacts at the far outfall location were marginally non-significant (Fig. 4, Table S5).

Evidence for recovery was mixed, and in some cases the two tests (before vs shutdown; discharging vs shutdown) gave inconsistent results. Cover of polychaetes and bryozoans at the near outfall location in the shutdown period was not significantly lower (relative to reference locations) than those in the before period, which suggests recovery (Fig. 4). However, neither group showed a difference when comparing the discharging and shutdown periods, suggesting impacts to source populations. Sponges did not recover according to either test.

In contrast, barnacles and hydroids increased in cover around the outfall while the plant was operating (Figs. 4 and 5, Table S5). Barnacle cover increased by 58% at the near outfall location, but decreased at the far outfall location. Hydroid cover remained similar at outfall locations from before to discharging periods, but decreased substantially at reference locations to create significant relative change (Figs. 4 and 5). Bivalve cover increased at both near and far outfall locations during operation (Figs. 4 and 5), although mean cover was low (<1%). Neither barnacles nor hydroids showed significant recovery at either outfall location, but bivalves appeared to recover at the near outfall location (Figs. 4 and 5, Table S5). The gradient of increased abundance was similar in both north and south directions for barnacles, stronger in the southern direction for hydroids (Fig. 6, Table S6). Cover of colonial and solitary ascidians showed no significant change in response to plant operation (Figs. 4 and 5, Table S5).

3.4. Species

Several species significantly decreased in cover around the outfall during plant operation, relative to change at reference locations (Figs. 4 and 6, Table S7 and S8). Species impacted at the near

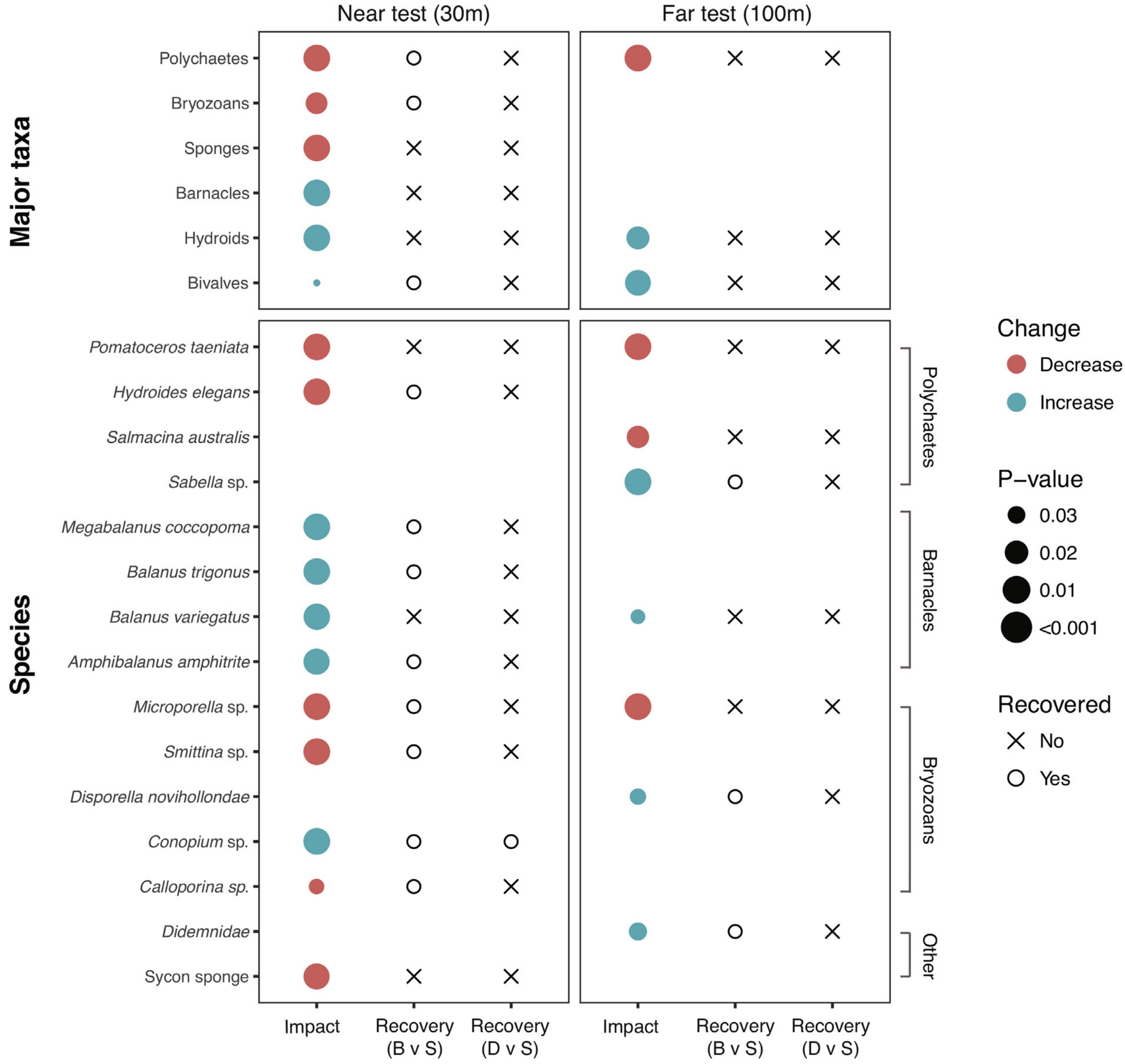

Fig. 4. Graphical summary of statistical results for tests of impact and recovery. Green points indicate an increase at outfall locations relative to reference locations, and red points a decrease. Only statistically significant ($P < 0.05$) tests for impact are shown. "Recovery (B v S)" tests for no difference ($P > 0.25$) between outfall/reference locations across before and shutdown periods. "Recovery (D v S)" tests for two conditions: (i) a difference ($P < 0.05$) between outfall/reference locations across during and shutdown periods, and (ii) that the mean cover in the shutdown period is closer to the before period than the discharging period. Missing symbols for some tests of recovery are due to model non-convergence. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

outfall location included two polychaetes (*Pomatoceros taeniata* and *Hydroides elegans*) and four bryozoa (*Microporella* sp., *Smittina* sp. and *Calloporina* sp.). Of these, *P. taeniata* and *Microporella* sp. decreased in cover at both outfall locations (Figs. 4 and 6, Table S7 and S8). Impacts were particularly strong and bidirectional for *Microporella* sp. (Fig. 6), while the gradient in impacts for other taxa varied between north and south directions (Fig. 6). There was mixed evidence of recovery for these species, except for *P. taeniata* where all tests indicated no recovery (Fig. 4). Species that increased in cover near the outfall included three barnacles (*Megabalanus coccopoma, Balanus trigonus, Balanus variegatus* and *Amphibalabus amphitrite*) and a bryozoan (*Conopium* sp.) (Figs. 4 and 7, Table S7 and S8). Of these, only *B. variegates* showed recovery relative to both before and discharging periods (Fig. 4).

3.5. Fish exclusion experiment

There were no trends indicating increased abundance of taxa in caged v uncaged treatments at outfall locations, compared to treatments at reference locations (Fig. S7). This was the case for the five major taxonomic groups examined. There were no differences in multivariate community structure between caging treatments between test and reference locations (Table S10).

4. Discussion

The high-pressure diffusers effectively diluted desalination brine to less than one psu of background salinity within 100 m of the outfall, reaching salinity levels that were highly unlikely to harm sessile invertebrates. A one psu increase is well within the salinity tolerance of most marine invertebrates (Bayly, 1972), including the impacted polychaete *Hydroides elegans*, which occurs in salinities as high as 42 psμ in the Aegean Sea (Kocak and Kucuksezgin, 2000). Water temperature was unaffected by the discharge, indirect effects of fish predation were experimentally demonstrated to be negligible, and chemicals used in the

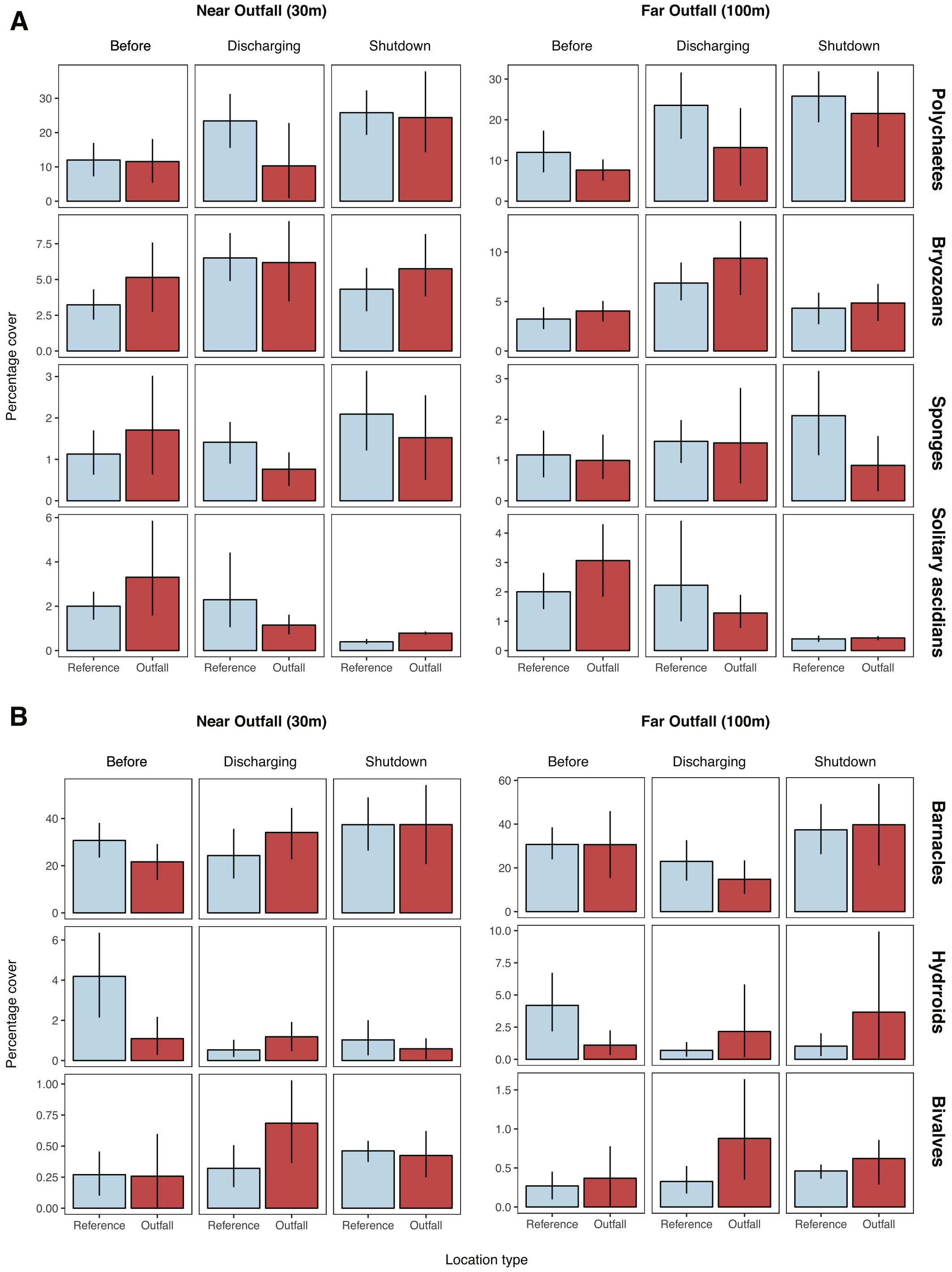

Fig. 5. Major taxonomic groups. Bars represent means across outfall and reference locations, and lines are bootstrapped 95% confidence intervals. Impact locations are either near (30 m from the outfall) or far (100 m from the outfall). (A) are taxonomic groups that reduced in cover near the outfall while operating, (B) are taxa that increased in cover.

desalination process are unlikely agents since their concentrations are minimal and their dilution proportional to that of the brine. However, clear impacts were still observed on sessile invertebrates, suggesting that effects of the desalination discharge were unrelated to any of the above stressors. Here we suggest that discharge velocities achieved by the high-pressure diffusers increased near-bed flow away from the outfall to the extent that it impacted the settlement, growth and survivorship of invertebrates.

High-pressure diffusers are designed to ameliorate hypersalinity by increasing mixing and thereby diluting effluent with surrounding seawater. The outfall in this study discharges effluent at a velocity of 5 m s^{-1} to achieve a dilution factor of 30 at 75 m from the outfall. High-pressure jets are only present in the immediate area of the diffuser, but elevated velocities may persist near the seafloor due to the entrainment of large volumes of surfaces waters for dilution (Fig. 1A). The outfall in this study discharges 365 ML/day of brine, and once diluted 30 times this equates to 130 m^{-3} flowing away from the diffuser. If brine flowed away radially from the outfall with a thickness of 5 m above the seafloor, this equates to a velocity of approximately 0.25 ms^{-1} at 30 m from the

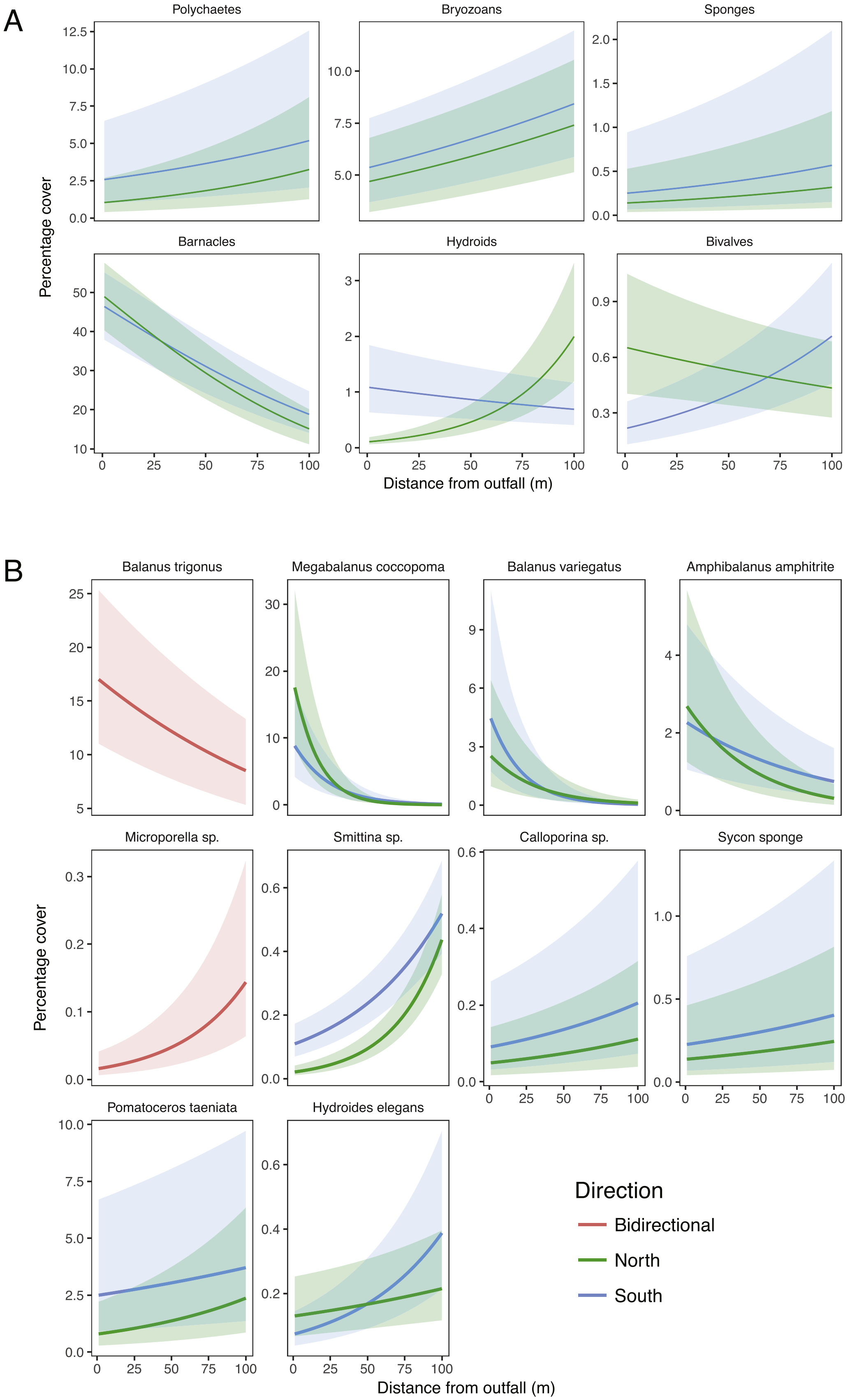

Fig. 6. Trends in cover with distance from the outfall. Panels show significant trends for (A) taxonomic groups and (B) species that showed impacts at near outfall locations in the MBACI test.

outfall, and 0.1 m s^{-1} at 100 m from the outfall. Before the outfall was constructed, the median near bed current measured at the site between May and July 2006 was 0.05 m s^{-1}, and 0.1 m s^{-1} was only exceeded 10% of the time (Miller et al., 2007b). Therefore, flow 100 m from the discharging outfall is approximately double that of ambient flow, and is sufficient to affect marine invertebrate settlement and feeding ability (Abelson and Denny, 1997; Railkin, 2004).

Support for flow as the dominant mechanism of impact can be found in the patterns of change in each taxonomic group. Some taxa benefited from the discharge while others suffered major declines, and patterns are consistent with the expected response of each taxonomic group to increased flow. Polychaetes were almost eliminated near the outfall when it first discharged, and sponges and bryozoans substantially reduced in cover. In contrast, barnacles proliferated and dominated communities near the operating outfall. We propose that impacts were related to the settlement ability (related to swimming speed), suspension feeding ability (specifically active, facultatively-active and passive suspension feeders), and evolved settlement preferences (i.e. in areas of fast or slow flow speeds or turbulent or laminar flow conditions) of marine invertebrate larvae in the flow conditions created by the desalination discharge.

Taxa vary in their ability to settle in flow, primarily due to differences in larval swimming ability. Stronger swimming larvae can settle in higher flow, while weak swimming larvae approximate passive particles and tend to settle in low flow conditions. Table S11 provides examples of swimming speeds of major taxonomic groups (adapted from (Railkin, 2004)), and these generally reflect patterns of impact around the outfall. For example, barnacles were the group that benefited most from the outfall, and have fast swimming larvae (almost 5 cm s^{-1}, Crisp, 1955) with known preference for settling in high flow (Crisp, 1955; Mullineaux, 1988; Qian et al. 1999, 2000). In contrast, polychaetes, the group most negatively impacted by the outfall, and have some of the slowest larval swimming speeds at 0.1 cm s^{-1} (Konstantinova, 1966). A laboratory study comparing the settlement preference of various species under a range of flow regimes found that a polychaete species avoided areas of high shear stress, a hydroid preferred high flow and shear stress conditions, and the response of bryozoans to flow varied between species (Mullineaux and Garland, 1993). In addition to their physical ability to settle in various flow regimes, species may also display evolved preference to settle in certain flow conditions due to factors such as feeding ability.

The ability of many filter or suspension feeders to capture food is highly sensitive to flow. Many polychaete species have delicate ciliated crowns (Jumars et al., 2015), and those observed in the current study were relatively small. Under higher flow speeds (>10 cms^{-1}), these suspension-feeders may be unable to feed effectively as they would likely retract their ciliated fans for protection against potentially damaging flow (Nash and Keegan, 2003). It may be that only the larger *Sabellid* species were sufficiently robust to benefit from the higher food delivery at the far (100 m) outfall sites. Bryozoans generally have difficulty feeding at flow >5 cms^{-1} (Genovese and Witman, 1999; Pratt, 2008), as they retract their lophophores (a ciliated tentacular organ) in a response likely related to feeding inefficiency and damage avoidance. This may explain the impact observed for this group, though some bryozoans benefitted near the outfall and laboratory tests have found some species prefer higher flow (Mullineaux and Garland, 1993). Established sponges (i.e. those already settled and of reasonable size) may feed better in higher ambient flow (Leys et al., 2011), though not in all cases (Ludeman et al., 2017). Nevertheless, it may be that for sponges, slow larval swimming speeds consequent difficulty settling in flow was a more important factor than feeding.

In contrast to the above taxa, barnacles are well-suited to feeding in higher flow and commonly occur in such conditions. In low flow, barnacles actively suspension-feed by waving their cirral fan though the water, but in higher flow can passively feed by orientating the cirral fan into the water flow (Trager et al., 1990). Of even greater significance is the ability of barnacles to rapidly reorientate the cirral fan in turbulent or oscillating flow (Trager et al., 1992), as may occur where dense brine tumbles to the seafloor. Many bivalve species are known to have faster growth rates in areas of higher flow (Fréchette et al., 1989; Wildish and Kristmanson, 1997), and while little research has been done on hydroids and flow, they too may benefit from higher flow and faster food delivery (Judge and Craig, 1997). Similarly, ascidians would be expected to benefit from higher flow (Knott et al., 2004; Railkin, 2004), but this was only reflected in the response of didemnid colonial ascidians at the far outfall location.

Ecological impacts observed in this study are most consistent with change in flow created by the high-pressure diffusers. If hypersalinity was the dominant mechanism of impact we would expect decreased settlement of most taxa to varying extents, whereas flow is the most likely mechanism to cause such substantial increases in the cover of certain taxa (e.g. barnacles). This has important implications for desalination projects that plan to use high-pressure diffusers to reduce ecological impacts, and engineers should consider surrounding near bed hydrodynamics together with reduction of hypersalinity in the design of new outfalls. In an area with strong background currents, the effect of a high-pressure diffuser may be small, but areas with lower background currents are the same areas where high-pressure diffusers are required for dilution. This may influence the choice of acceptable outfall sites and defining the size of the regulated mixing zone.

Hydrodynamics may also affect recruitment through barotrauma as larvae are carried by the high-pressure jets, or through entrainment of larvae from the upper water column to the seabed. The local down-welling caused by the outfall transports shallow larvae to depth, changing larval composition near the seabed. Under natural conditions, the vertical distribution of larvae is related to their phototaxis (movement in response to light), which differs between major taxonomic groups (Thorson, 1964). Barnacles typically reside in the upper water column throughout their larval phase, while sponges and bryozoans begin at the surface before migrating downwards to settle. The circulation pattern created by the outfall may create abnormally high densities of barnacle larvae near the seabed, potentially affecting recruitment patterns. Redistribution of larvae is unlikely to be a major cause of impacts compared to effects of flow on settlement, but may contribute to some extent.

The lack of post-operation recovery for some taxa suggests that change to recruitment over the 12-month discharging period had ongoing effects on populations around the outfall. This may be if localised patterns in recruitment created by the outfall affected the distribution of subsequent generations, or if high flow prevented effective feeding in adult populations and reduced their abundance. Some adult mortality may also be caused by hypersalinity close to the outfall, particularly when the plant was first discharging and brine seeped from a diffuser. Alternatively, lack of evidence of recovery may reflect low statistical power for these tests. Statistical support for recovery was inconsistent for some taxa, which may be due to differences in statistical power between the two types of test for recovery (Downes et al., 2002). In the test of recovery that compared before vs. shutdown periods, a non-significant result (i.e. no difference) suggests recovery and may be misleading in situations with low statistical power. In contrast, the test of discharging vs. shutdown requires a significant difference, and therefore more statistical power, to infer recovery. No major taxonomic groups and only one species recovered according the discharging vs. shutdown test, so statistical power was almost certainly a limitation. Conclusively demonstrating recovery remains challenging, particularly when sampling is temporally constrained.

Despite the obvious and consistent changes in communities near the outfall, it is important to interpret impacts in a wider context. There was not a large or persistent loss of biodiversity, but rather a localised redistribution of species in response to environmental conditions that are within the range of natural variability. The change in flow was analogous to the natural difference experienced by reefs that occur on exposed headlands versus those on sheltered reefs, and thus support different communities. Additionally, sessile invertebrates are one of several major faunal groups, and other groups such as fishes are unlikely to have been affected by flow to this extent. In contrast, impacts caused by hypersalinity welling on the seabed may be considered more sinister, since this is likely to extend to other groups and are beyond the range of natural variability. The high-pressure diffusers were successful in ameliorating what is arguably the greatest potential stressor of brine, but engineers should remain mindful of side-effects to this management strategy.

5. Conclusions

The ecological impacts resulting from desalination brine appeared to be driven by the increased flow created by the high-pressure diffusers, rather than by hypersalinity or other potential stressors. Growth in the number and size of desalination plants worldwide, combined with a transition to reverse osmosis technology, means that impacts of desalination plants to the marine environment are likely to become increasingly common. It is vital to better understand both the nature and mechanisms of impacts, particularly if current impact reduction strategies are themselves creating impacts. This study is the first to provide a before-after test for impacts of a desalination outfall on marine invertebrates, and to demonstrate that impacts near a high-pressure diffuser are likely caused by hydrodynamics rather than hypersalinity.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.watres.2018.08.071.

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