



La Niña Pushes an Endangered Temperate Soft Coral Species to the Brink of Localised Extinction

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Abstract

Extreme weather events such as floods are becoming more frequent, and pose a substantial threat to Australia's nearshore marine communities. In March 2021, a 450 km stretch of the eastern NSW coastline experienced a La Niña-related rainfall event over several days, resulting in large volumes of freshwater ingress to marine systems. Port Stephens, an estuary 250 km north of Sydney, recorded its highest week of rainfall on record. This was followed by two more flood events in March 2022 and June 2022. Prior to 2021, the marine-dominant Eastern Port of Port Stephens was home to the world's largest aggregations of *Dendronephthya australis*, an endangered species of soft coral endemic to the south-east coast of Australia. Using data from a 2019–2022 *D. australis* monitoring program in Port Stephens, spanning the unprecedented series of flood events in 2021–2022, we detail the impacts of flood events on the population. Prior to the floods, aggregations of colonies were persisting, and individuals were growing at two of the four monitored sites. However, flooding in March 2021 caused a 91% decline in the remaining areal extent of *D. australis*. Modelling of likely causative factors highlighted water depth as the most significant environmental variable correlated with coral loss. Corals in shallower waters experienced lower salinity and were the most impacted. Continued monitoring during 2021 and 2022 documented the loss of all remaining aggregations in the estuary after further La Niña-related rainfall events, to the point where *D. australis* is now on the brink of localised extinction.

Keywords Climate change · Conservation · *Dendronephthya australis* · Estuarine health · Flooding

Introduction

The epoch in which we are currently living — the Anthropocene — marks a time during which species extinctions are occurring at an alarming rate (Barnosky 2014; He and Silliman 2019). Climate change is triggering an increase in temperatures and severe storm events, which, coupled with intensifying human activity, is exacerbating the decline of both terrestrial and

marine ecosystems around the world (Dale 1997; Doney et al. 2012; Selwood et al. 2015). For the majority of Australia, La Niña is associated with climatic conditions with higher-than-average rainfall, which can lead to severe flood events (Bureau of Meteorology 2016). During March 2021–July 2022, coastal communities in New South Wales (NSW) experienced numerous La Niña-related flood events (Bureau of Meteorology 2021a, b, 2022). These floods impacted nearshore reefs in south-east Australia which were already exposed to a multitude of stressors, including sedimentation (Wainwright 2011); pollution (Ling et al. 2018); warming water (Wernberg et al. 2016); fishing (Stuart-Smith et al. 2008); boating activities (Glasby and West 2018); and severe wildfires (Barros et al. 2022). Consequently, threatened species reliant on these ecosystems have increasingly been impacted, with reduced opportunities to recover between disturbance events.

The ingress of large volumes of freshwater into estuaries and embayments during floods can have devastating impacts on marine-acclimatised fauna, including macroalgae (Davis et al. 2022) and corals (Coles and Jokiel 1992; Jokiel et al. 1993; Cardoso et al. 2008). Due to the hydrological

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characteristics of estuaries, salinities within these environments are inherently variable. However, organisms that thrive in marine-dominated zones within estuaries can experience mortality if salinity drops below critical physiological thresholds for extended periods of time (Parada et al. 2012; Saraswat et al. 2015). Whilst previous studies have investigated salinity tolerances of some marine taxa in estuaries, such as sponges (Fell et al. 1989), seagrasses (Benamina et al. 1999), and kelp (Davis et al. 2022), no known studies have assessed the salinity tolerance envelopes for soft corals (Malacalcyonacea). Previous work with hard corals (Scleractinia) suggests that salinity tolerances vary between coral species, but there are consistently high mortality rates when exposed to salinities of ~17 PSU for up to 48 h (Edmondson 1928; Coles and Jokiel 1992; Moberg et al. 1997; Berkelmans et al. 2012). Floods in urbanised areas can also increase contaminants introduced to estuaries such as nitrates (Sigleo and Frick 2007), sewage (Hart et al. 2020), metals and metalloids (Conrad et al. 2020), pesticides (Laicher et al. 2022) and per- and poly-fluoroalkyl substances (PFAS) (van Leeuwen et al. 2019). Pollutants can have deleterious effects on marine organisms throughout the food web, potentially resulting in fish kills (Adams et al. 2020) and morbidity or mortality of benthic fauna (Diaz and Rosenberg 2001; Jamal et al. 2022).

During 2021–2022, three La Niña-related flood events resulted in the influx of large volumes of freshwater into embayments and estuaries on the south-east coast of Australia (Bureau of Meteorology 2021a, b, 2022). The reduction in salinity associated with these events substantially impacted shallow reef communities, including kelp habitats (Davis et al. 2022), and here we detail their impact on *Dendronephthya australis*, an endangered species of soft coral in Port Stephens, NSW, Australia; the only location where this species has previously been recorded in large abundances (Poulos et al. 2013, 2016).

Dendronephthya australis is a habitat-forming species, endemic to the temperate waters of south-eastern Australia (Verseveldt and Alderslade 1982). For over 50 years, aggregations of the soft coral provided habitat for a large range of marine species (Verseveldt and Alderslade 1982), including the Endangered White's seahorse *Hippocampus whitei*, and juveniles of the fishery-important Australasian snapper *Chrysophrys* (Poulos et al. 2013; Harasti et al. 2014; Corry et al. 2018). Biodiversity of rocky reef fauna has previously been correlated with structural benthic complexity (Fulton et al. 2016; Quaas et al. 2019), particularly within estuarine environments (van Lier et al. 2017), with structure providing refuge sites for both vertebrates and invertebrates, thus contributing to a more complex food web (Alvarez-Filip et al. 2011). Soft coral aggregations not only provide structure and shelter for fishes (Poulos et al. 2013; Harasti et al. 2014), but they also host a range of epifaunal organisms such as small

crustaceans and molluscs (Cúrdia et al. 2015; Davis et al. 2018; Steinberg et al. 2020; Finlay-Jones et al. 2021; Larkin et al. 2021a), which are often prey for small fishes (Hacunda 1981; Edgar and Shaw 1995).

Prior to the 2021–2022 flood events, the Port Stephens *D. australis* population was in rapid decline at two of the four key aggregation sites in this estuary (Larkin et al. 2021b). Subsequent to this documented decline, the geographically restricted soft coral was listed as endangered in 2021 (NSW Fisheries Scientific Committee 2021) and a top 100 priority species within the Australian Commonwealth's Threatened Species Action Plan in 2022 (Department of Climate Change, Energy, the Environment and Water 2022). Despite the overall decline of *D. australis* in the Port Stephens estuary, the two remaining aggregations covered an areal extent of ~7,900 m² (Larkin et al. 2021b), comprising thousands of healthy colonies.

This study details findings from a tagging programme that provided insights into natural growth and attrition rates of *D. australis* colonies between 2019 and 2021. Observations during this programme captured the effects of a major flood event on the soft coral population in 2021, triggering additional mapping efforts throughout 2021–2022 to document the estuary-wide flood impacts. Results from the tagging and mapping programmes detailed in this study provide a greater understanding of population dynamics and highlight the vulnerability of this endangered species to severe weather events.

Methods

Study Site

Port Stephens is a large (135 km²) estuary, located ~250 km north of Sydney, NSW (Fig. 1). The estuarine embayment is situated within the 4,480 km² Karuah catchment, with the largest freshwater inflows from the Karuah River. Channels on the southern side of the Eastern Port provide a pathway for strong tidal currents, which supply food and nutrients to a plethora of suspension-feeding organisms (Poulos et al. 2013; Davis et al. 2015a). Previous studies identified four aggregations of *D. australis* in the embayment at Sandy Point, Redpatch Point, Pipeline and Nelson Bay Beach (Fig. 1); these are the primary focus sites for ongoing studies. Each of these locations once hosted hundreds to thousands of colonies just 4 years prior to this study (ML, Pers. Obs). As *D. australis* is a gonochoric broadcast spawner (Larkin et al. 2023b), clustering of colonies is important for the persistence of the species. The presence of multiple neighbouring colonies increases the chance of representation by both sexes, thus increasing the likelihood of successful sexual reproduction. The definition of an 'aggregation'

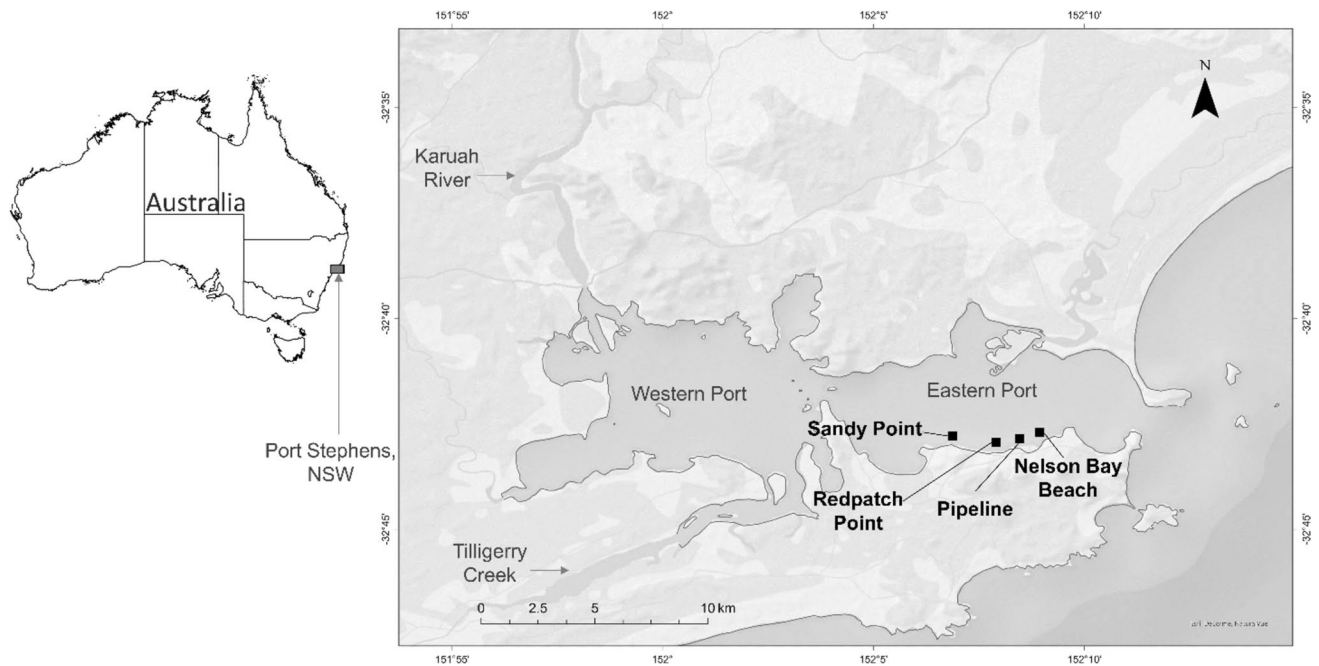


Fig. 1 Key locations inside the estuary where *Dendronephthya australis* aggregations were found historically (in black), and other significant locations within this study (in grey); Port Stephens, NSW, Australia

within this study, and in Larkin et al. (2021b), is defined as a cluster with a minimum of five colonies within close proximity to each other ($\leq \sim 3 \text{ m}^2$). A video demonstrating a typical aggregation can be viewed in the Supplementary information (SM1).

Colony Growth and Survival

To determine lifespan and growth rates of colonies within the Port Stephens *D. australis* population, we carried out monthly tracking of colony growth and survival over an 18-month period (September 2019–February 2021) at the four sites with *D. australis* aggregations (Fig. 1). Galvanised steel pegs with cattle tag identifiers were installed amongst colonies at the four aggregation sites. A total of 99 colonies were tracked, comprising of 29 colonies at Redpatch Point, 29 at Sandy Point, 27 at Pipeline and 14 at Nelson Bay Beach. To monitor growth, all crowns of colonies immediately adjacent to the pegs were measured in a north–south, then in an east–west direction. These diameters were used to calculate the average crown diameter. As *D. australis* colonies have hydroskeletons that expand and contract within tidal cycles (Davis et al. 2015b), measuring colony size and growth is a challenge (Fabricius et al. 1995). To reduce this variability between surveys, diameters were recorded at slack high tide every 4–6 weeks, to determine average colony growth rates over the 18-month timeframe. Polyp counts have previously been identified as an optimal method of measuring growth rates of *Dendronephthya* (Fabricius

et al. 1995); however, this method is difficult to apply to large colonies comprising $> \sim 100,000$ polyps (Larkin et al. 2023b), and was therefore considered as unfeasible for this study. To monitor survival, top-down photographs were obtained at each tag site (Fig. 2), and colony reference IDs were assigned to individual colonies. The depth of sand (against the tag peg), colony reference ID, and the average diameter of surviving colonies were recorded in each survey.

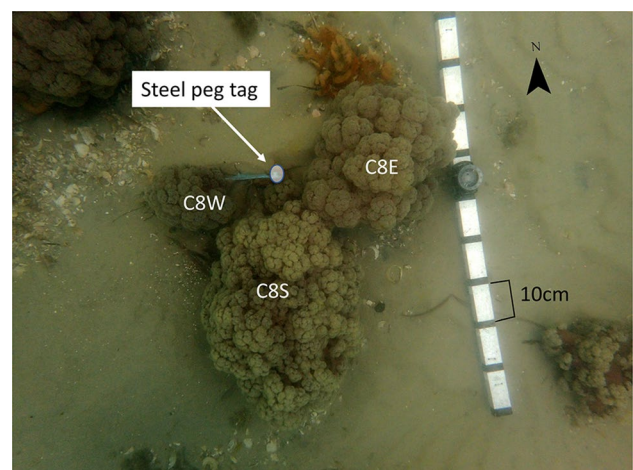


Fig. 2 A top-down photograph example of the *Dendronephthya australis* monitoring tag C8, with a scalebar, compass, and tag in the image. Colonies were labelled with reference IDs according to their position adjacent to the tag (e.g. C8W: C=Sandy Point, Corlette; 8=Tag 8; W=West)

Mapping

To define the impact of floods on the areal extent of *D. australis* aggregations, mapping was conducted at the aggregation sites at Redpatch Point and Sandy Point, both before the flood event in February 2021 and after the floods in April 2021, November 2021 and July 2022. Aggregations at the Pipeline and Nelson Bay Beach sites were not included as they disappeared during 2019 (Larkin et al. 2021b). Mapping was conducted using diver-towed video transects, using an Olympus TG6 camera in PT-059 housing. Additionally, more remote locations were mapped using a SplashCam Deep Blue vessel-based towed video camera (www.splashcam.com/product/deep-blue-pro/). Both diver and vessel-based mapping utilised a Garmin GPS (GPSMAP 78SC) to determine GPS positions. These data were compared against transects conducted in all areas where *D. australis* aggregations were found, from an extensive mapping program conducted in 2019 (Larkin et al. 2021b).

Flood Events Data

To obtain salinity and temperature data at the depth and location of a thriving soft coral aggregation, a HOBO U24-002-C Conductivity Data Logger (<https://www.onsetcomp.com/products/data-loggers/u24-002-c>) was installed at Redpatch Point (Fig. 1) in early March 2021. Data were retrieved from the data logger from 8/3/21 to 3/4/21 to assess the impacts of the March 2021 flood event on these water parameters. As the remaining *D. australis* aggregations were < 2 km apart at this time, and in the same depth range (5–8 m), one logger at the site furthest from the Karuah River discharge point (Redpatch Point) was deemed sufficient to provide salinity data for this event. To analyse the magnitude of the flood events during 2021–2022, river discharge data were accessed from Water NSW (<https://realtime.data.waternsw.com.au>).

Water depths were obtained from 2018 bathymetric data (NSWDPIE 2019), which also formed the basis of slope and current velocity calculations. Maximum velocity values were modelled using the TELEMAC 2-D hydrodynamic analysis package (Hervouet 2000; www.opentelemac.org). Slope values were obtained using the ‘surface’ function in ArcMap 10.5.1. ‘Distance from shore’ and ‘distance from estuary mouth’ were calculated in ArcGIS Pro (v.2.9.0), using the ‘Multiple ring buffer’, and ‘Near’ functions respectively. Random points (minimum 0.5 m apart) were produced using the ‘Create random points’ function in ArcGIS Pro (v.2.9.0), simulating *D. australis* colony presence in 2019 and 2021. These points were used to intersect the variable rasters using the ‘Extract multi values to points’ tool in ArcGIS Pro, providing the basis for modelling.

Analyses

To compare survival of *D. australis* colonies by site over the 18-month study period, Kaplan-Meier survival estimation analyses were conducted in R, using ‘survival’, ‘survminer’ and ‘dplyr’ packages (RStudio Team 2020). Linear regressions of changes in the average diameter of individual colonies were plotted to visualise trends of growth between survey months for surviving colonies at each site.

Distance based linear models (DistLM) were generated in PRIMER7 (Anderson et al. 2008) to determine which variables best-explained coral losses between 2019 and 2021. Five explanatory variables were examined based on their previously identified importance to presence of *D. australis* (Poulos et al. 2016; Larkin et al. 2021b). These comprised depth; distance from shore; distance from estuary mouth; slope; and current velocity. All five variables were considered in models using Euclidean distance similarity matrices with the ‘BEST’ model selection procedure to identify the most parsimonious model, using AIC selection criteria (Anderson et al. 2008). The contribution and statistical significance of each variable was determined using marginal tests. All variables tested were within the acceptable collinearity range (< 0.7, and > -0.7) (Anderson et al. 2008).

Results

Colony Growth and Survival

The average *D. australis* colony diameter varied between sites at the start of the soft coral monitoring program in September 2019. Site average colony diameters (cm ± SE) were Sandy Point — 16.0 ± 1.3 cm; Redpatch Point — 21.2 ± 2.0 cm; Pipeline — 10.2 ± 1.2 cm; and Nelson Bay Beach — 11.1 ± 1.4 cm.

D. australis colonies at Sandy Point and Redpatch Point survived for the entire pre-flood study period (September 2019–February 2021), and colony diameters increased over this period (Fig. 3). By contrast, colonies at Pipeline were last observed alive after 189 days of monitoring, and declined in diameter during that time. Similarly, colonies at Nelson Bay Beach were observed alive for 258 days, and diameters declined over that period (Fig. 3).

Kaplan-Meier survival analyses showed a significant difference ($P < 0.001$) in survival of colonies between the four study sites over the 18-month pre-flood study period. There was a gradual decline in the number of colonies at all sites due to mortality (Fig. 4). Average mortality rates per day were 0.47% at Pipeline, 0.35% at Nelson Bay Beach, 0.18% at Sandy Point, and 0.17% at Redpatch Point. At Sandy Point and Redpatch Point, mass mortality of the remaining colonies coincided with the flood event in March 2021 (Fig. 4).

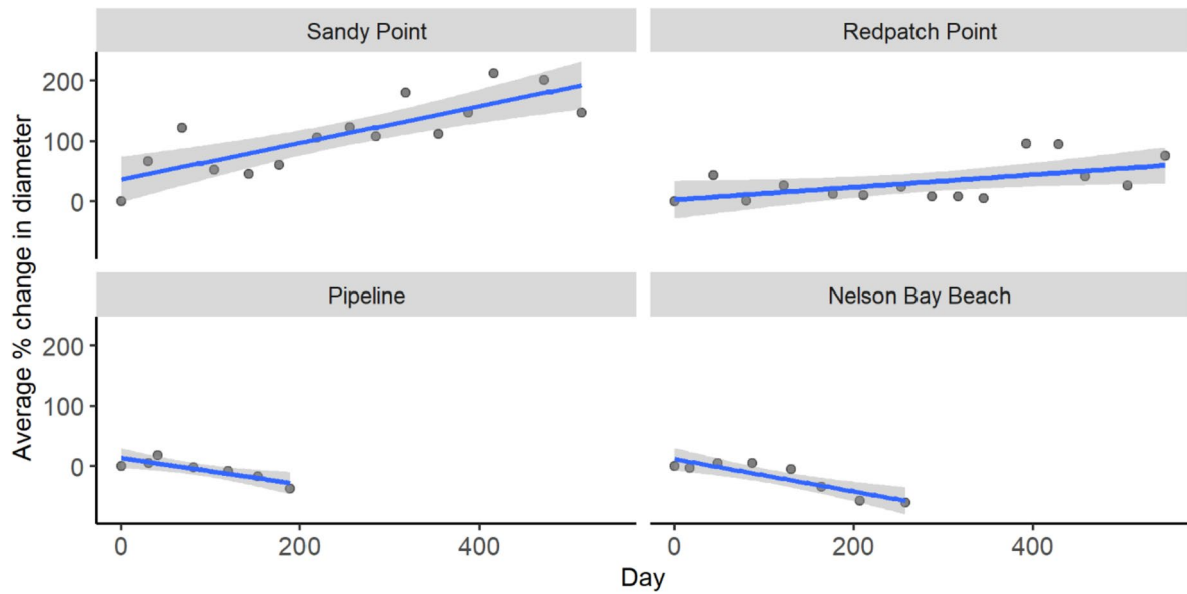


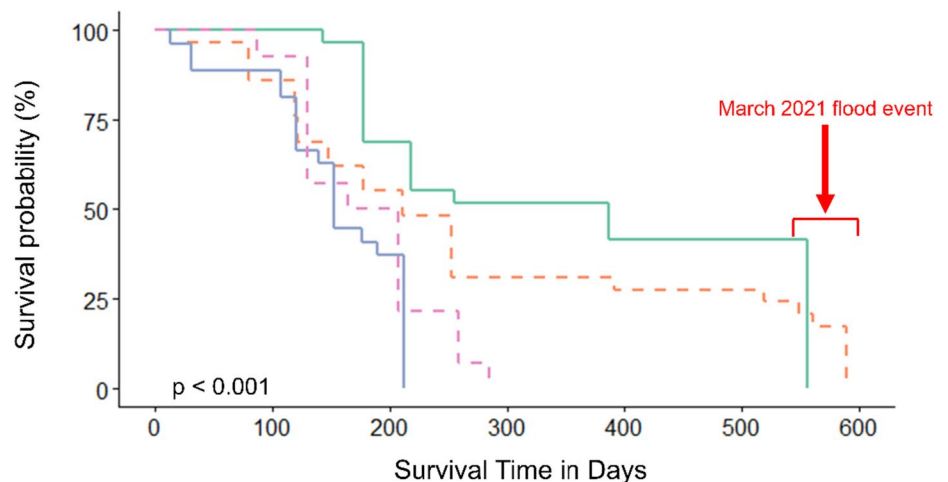
Fig. 3 Linear regressions (+95% CI) of average % change in *Dendronephthya australis* colony diameter at four locations within Port Stephens estuary

Mapping

Mapping conducted after flooding, in April–November 2021, indicates that the areal extent of *D. australis* aggregations had fallen to ~851 m² (Fig. 5), a ~91% decline compared with the pre-flood areal extent in February 2021 (9,300 m²) (Larkin et al. 2021b). This equates to just 3% of the area of aggregations in 2011 (28,600 m²) (Poulos et al. 2016). Bare sand was the only visible substrate at the locations

where colonies were previously found. Of the estimated 6,140 colonies that were present in the Port Stephens estuary in 2019, only ~185 remained after the 2021 flood event (ML, pers obs). Particularly noteworthy was the complete absence of *D. australis* colonies in water shallower than 8 m after the March 2021 flood. Subsequent mapping in June 2022 confirmed the complete disappearance of these remaining aggregations and, as of September 2023, there are no longer any *D. australis* aggregations within the

Fig. 4 Kaplan-Meier survival plot of the four key *D. australis* aggregation sites within Port Stephens, showing survival of colonies monitored over a 600-day period. The red arrow and brackets indicate the timing of the March 2021 flood event (surveys were not completed on the same day at each site)



	Number at risk						
	0	100	200	300	400	500	600
Sandy Point	29	29	20	15	12	12	0
Redpatch Point	29	25	16	9	8	8	0
Pipeline	27	24	10	0	0	0	0
Nelson Bay Beach	14	13	7	0	0	0	0

Site — Sandy Point — Redpatch Point — Pipeline — Nelson Bay Beach

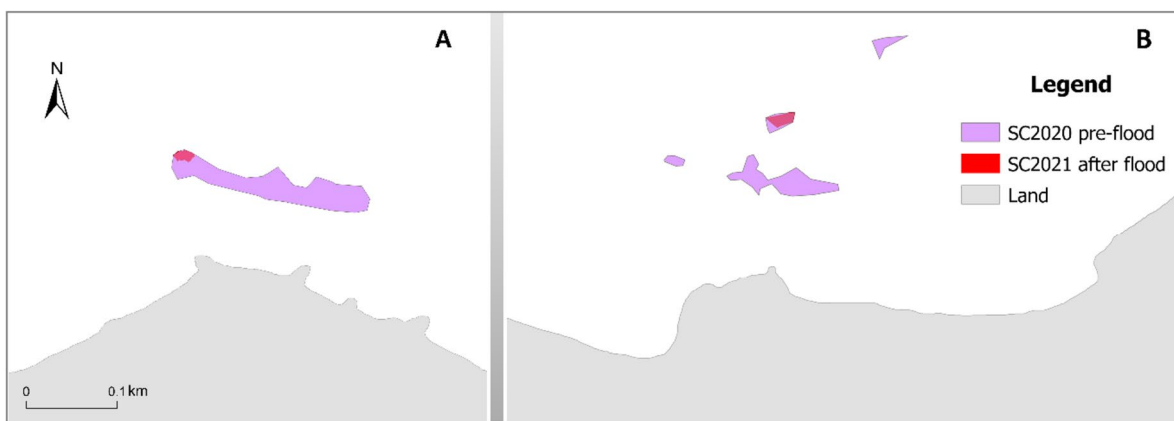


Fig. 5 Aggregations at (A) Sandy Point and (B) Redpatch Point showing the pre-flood *Dendronephthya australis* areal extent (purple shading) in Feb 2021 and post-flood in April 2021 (red shading). By July 2022, all *D. australis* aggregations had disappeared

Port Stephens estuary, just isolated individual colonies. Ad hoc diving surveys conducted between June 2022 and September 2023 confirm that no new aggregations have formed.

Flood Events

Data from the Port Stephens region show that the rainfall in March 2021 and the associated flooding was a historic weather event (Bureau of Meteorology 2021). The data show that Nelson Bay received a total of 649 mm rainfall over ten consecutive days (March 15–24 inclusive). Discharge data from the estuary’s largest freshwater source (the Karuah River) indicate that March 2021 was the third

largest month of average daily discharge, recording a rate of 9,623 megalitres per day (ML/day) (Fig. 6). The next largest month of discharge since records began in 1969 was in 1990 with an average rate of 9,997 ML/day, and the largest 15,399 ML/day in 1971. La Niña-related rainfall continued throughout 2022, with further flooding in the Karuah catchment in March and July, as indicated by high discharge rates from the Karuah River (Fig. 6). Since records began in 1969, the 2-year Karuah River rolling average discharge rate is 1.4 million ML. The 2021–2022 period saw a record of 5.3 million ML; exceeding the previous record from 1989 to 1990 (4.1 million ML) by ~ 1.2 million ML.

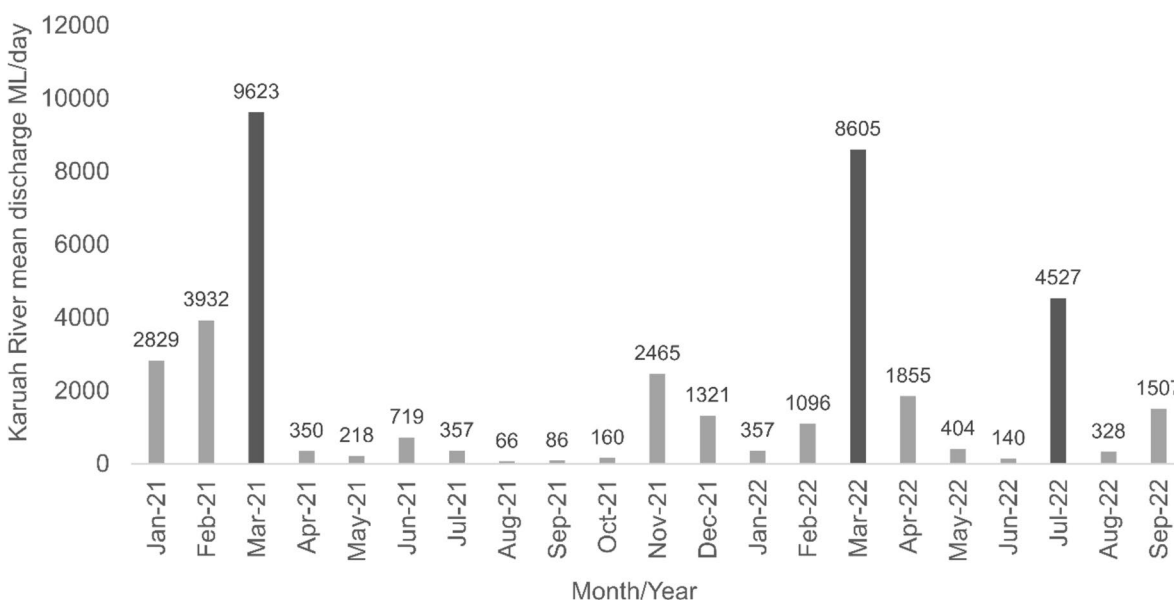


Fig. 6 Discharge rates from the Karuah River; the largest upstream river from the Port Stephens estuary during 2021–2022. Darker bars indicate the average flow rates over the months that flooding occurred (March 2021, March 2022, and July 2022)

Prior to the flood event in March 2021, salinities from 6 m depth at Redpatch Point were essentially marine 33–35 PSU (Fig. 7). During the flood event, salinity reached a low point of 6.9 PSU (measured over a 30-min period) on 22nd March 2021, which was the seventh day of the rain event (Fig. 7). Fluctuations to levels below 10 PSU occurred for 3 days, returning to ‘normal’ (with all salinity readings > 30 PSU) from 29th March, some 14 days after the heavy rainfall began. The water temperature ranged from 18.8 to 21.9 °C during this rainfall event (Fig. 7), which was within the typical range for Port Stephens at this time of year (Davis et al. 2017).

Environmental Drivers of Coral Losses During Flooding

Marginal tests demonstrated that all variables except the average maximum velocity were significant, but most parameters explained a small proportion (< 10%) of the variation in coral loss — the exception being depth which explained 43.5% alone (Table 1). The most parsimonious (‘BEST’) DistLM, to explain soft coral loss following the flood in March 2021 included three variables; depth, distance to shore and slope, and accounted for 45.68% of the variation in coral loss (Table 2).

Discussion

Climate change and anthropogenic activity are contributing to species extinctions at an alarming rate (Ceballos et al. 2015). This study details the complete loss of *Dendronephthya australis* aggregations in the Port Stephens estuary, NSW; historically the most prolific location where this

Table 1 Marginal tests for the relationship between individual environmental variables and soft coral loss between 2019 and 2021

Variable	SS (trace)	Pseudo- <i>F</i>	<i>P</i>	Proportion (%)
Depth	151.18	4192	0.0001	0.435
Distance shore	22.346	374.06	0.0001	0.064
Slope	5.1329	81.602	0.0001	0.015
Distance estuary	4.74	75.27	0.0001	0.014
Velocity	0.18472	2.8948	0.0853	0.0005

species occurred. Not only do we provide further evidence of continued declines in Port Stephens, following on from studies by Harasti (2016) and Larkin et al. (2021b), we also document the impacts of a flood event (March 2021) that caused significant mortality of the coral aggregations that were still persisting prior to the flood. Significant rainfall and related flooding in March 2021 caused widespread damage to other rocky reef habitats in NSW (Davis et al. 2022), and we demonstrate that the flood impacts included mass mortality of *D. australis* colonies within Port Stephens. By November 2021, only 851 m² of *D. australis* habitat remained in Port Stephens, and by July 2022, after two additional flood events, there were no longer any *D. australis* aggregations remaining in Port Stephens, although a few solitary colonies persisted at isolated locations within the estuary (ML Pers. Obs.).

Prior to the March 2021 flood, loss of *D. australis* at the Pipeline and Nelson Bay Beach aggregation sites had already occurred. In the lead-up to the disappearance of corals at these sites, colony diameters were declining, suggesting that conditions were no longer suitable for growth and survival.

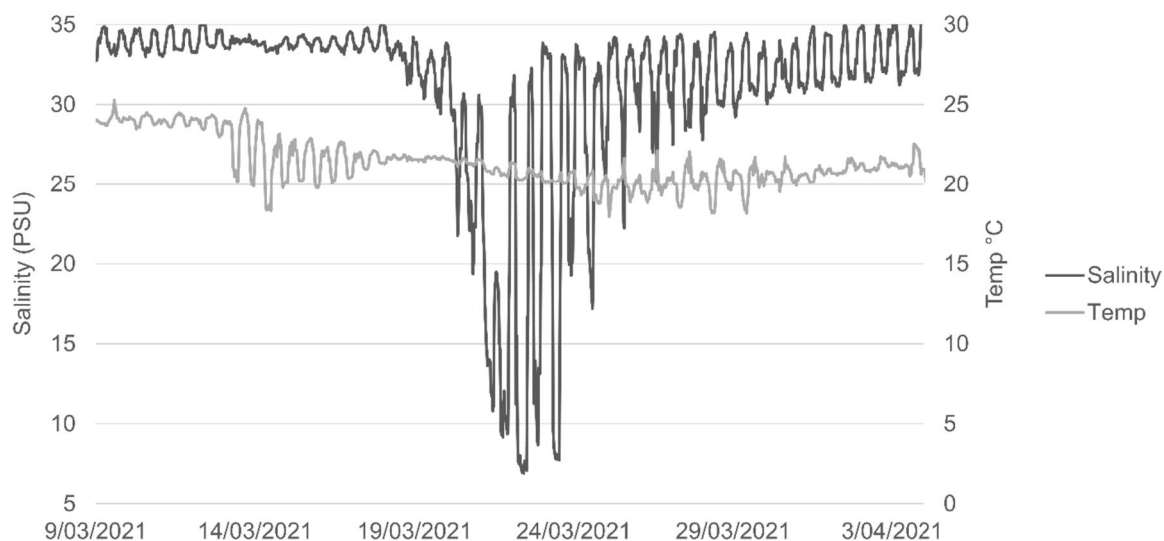


Fig. 7 Salinity and temperature in Port Stephens estuary over a 3-week period, which included the dates of substantial rainfall from 15th to 24th March, 2021

Table 2 Results of ‘overall best solutions’ for DistLM models assessing variables influencing coral loss between 2019 and 2021

AIC	R^2	RSS	No. Vars	Selections
– 18294	0.4568	188.73	3	Depth, Distance shore, Slope
– 18293	0.45689	188.7	4	Depth, Distance shore, Slope, Velocity
– 18292	0.4568	188.73	4	Depth, Distance shore, Slope, Distance Estuary
– 18291	0.45689	188.7	5	All

The most parsimonious test is in bold, comprising three variables

Depth water depth, *dist shore* distance from the shoreline, *slope* slope of seafloor, *velocity* average maximum velocity of current, *dist estuary* distance from the estuary mouth

As identified in Larkin et al. (2021b), it is likely that sand movement was a major contributing factor to colony decline in these areas. In contrast, within the aggregations at Redpatch Point and Sandy Point prior to the flooding, colonies increased in size and the overall areal extent remained stable between late 2019 and February 2021. Kaplan-Meier analyses indicated that mortality occurred at all sites, with mortality rates for colonies at Sandy Point and Redpatch Point prior to the flood events providing an indication of the rate of natural attrition, with mortality rates averaging 0.17% per day at these sites. Monitoring data also provided important new information on *D. australis* life expectancy, with some colonies surviving for at least 589 days; this indicates that *D. australis* has the potential to live for at least 1.5 years in the wild.

Models examining the environmental variables correlated with colony mortality between February and November 2021 found that depth, distance from the shore, and slope all contributed to the ‘BEST’ model. Depth made the greatest contribution to explaining flood-induced mortality, with post-flood surveys finding that only colonies present in depths > 8 m survived the March 2021 flood event. This can be explained by the density variance between fresh and sea water; when a plume of less dense fresh water combines with seawater in an estuary, it creates a lowered ‘surface salinity’ effect (Barros et al. 2014). Hence, *D. australis* aggregations in shallower depths were exposed to low salinities during the flood event. The influx of large volumes of low salinity water, even for brief exposure times, can have lethal impacts on marine life, including corals (Coles and Jokiel 1992; Dias et al. 2019). As salinities were measured at Redpatch Point, which was the easternmost aggregation site (furthest away from the Karuah River), it is highly likely that the salinity levels were similar, or lower, at Sandy Point (the aggregation site closer to the freshwater source, and furthest away from the ocean). These findings are consistent with the impacts recorded on kelp at shallow depths (< 10 m) at multiple sites in the Port Stephens estuary as a result of the March 2021 flood event (Davis et al. 2022). The severity of impacts on kelp decreased at sites closer to the entrance to the embayment (Davis et al. 2022), supporting the hypothesis that the freshwater ingress (and any associated contaminants) had a greater impact on the westernmost sites in the estuary.

Although mortality of *D. australis* as a result of sudden freshwater ingress has been recorded previously during an aquarium-based experiment (Poulos 2011), aggregations have persisted in the Port Stephens estuary despite prior instances of flooding over the past 50 years. Salinity has not been recorded at the soft coral aggregation sites during historical flood events, so the precise salinity tolerance levels for this species are not known. The salinity levels measured at Redpatch Point during the March 2021 flood show that there were 22 cumulative hours measured at < 10 PSU, 46 h measured < 20 PSU, and a total of almost four days < 30 PSU (Fig. 7). The data available for local rainfall indicate that this event was unprecedented, recording the largest ever volume of rainfall in consecutive days in Port Stephens (Bureau of Meteorology (2023) ‘Climate data online – daily rainfall’ available at <http://www.bom.gov.au/climate/data/>). These rainfall records, coupled with the Karuah River discharge rates (Fig. 6), demonstrate the unprecedented magnitude of this event within the Port Stephens estuary.

During the past 50 years, substantial clearing of vegetation has occurred in the Karuah catchment as well as on the southern foreshore of Port Stephens (Supplementary information SM2). Clearing of land for agriculture not only alters hydrodynamics within a catchment, it can also increase bank erosion, resulting in increased sedimentation downstream (Freeman et al. 2019). Whilst sedimentation could have contributed to the demise of *D. australis* aggregations during the 2021–2022 flood events, there was no evidence to suggest that the colonies were buried, as sand levels adjacent to the pegs at the monitoring sites did not change substantially (ML, Pers. Obs). However, as these measurements didn’t account for mobilised sediments in the water column, sand scour could have been another factor contributing to the colony decline. As *D. australis* is an azooxanthellate soft coral, the impact of turbidity is likely to be much lower than for zooxanthellate corals containing symbiotic algae that are reliant on photosynthesis (Bessell-Browne et al. 2017). However, sediment movement in the water column can impact the ability of azooxanthellate corals to feed (McClanahan and Obura 1997), and can affect larval survival and settlement success (Ertfemeijer et al. 2012).

Urbanisation on land adjacent to estuaries such as Port Stephens can lead to an increase in volume, rates, and

magnitude of water runoff into waterways (Hopkinson and Vallino 1995), and also alters catchment nutrient inputs. Flood events can intensify the ingress of anthropogenically derived pollutants into estuaries (Jeng et al. 2005; Wetz and Yoskowitz 2013), which can include faecal-derived bacteria (Lewis et al. 2013); nutrients such as phosphorus and nitrogen (Eyre and Twigg 1997); metal(loid)s (Coates-Marnane et al. 2016); and per- and polyfluoroalkyl substances (PFAS) (Taylor 2019), amongst others. Whilst previous studies have quantified the presence of nutrients and metal(loid)s within Port Stephens-based oysters (Gifford et al. 2005), and PFAS within oysters and fish (Taylor et al. 2018), there are no known studies that elucidate the effects of flooding on these pollutants within the estuary. Similarly, historical data demonstrate that the sewage-associated bacteria enterococci can be variably present in high quantities within Port Stephens (www.environment.nsw.gov.au/beachapp/report_enterococci.aspx), though no data were recorded inside the estuary during the 2021–2022 flood events. Although the impacts of pollutants haven't been documented for *D. australis* specifically, instances of morbidity and disease of other coral species have been correlated with pollutants in waterways (Kaczmarek and Richardson 2011; Chan et al. 2012; Redding et al. 2013; Yoshioka et al. 2016). Whilst the disappearance of the majority of *D. australis* colonies at Redpatch Point and Sandy Point coincided with the low salinities associated with the March 2021 flood event (Fig. 7), it is possible that other factors associated with flooding, such as pollution, contributed to their mortality during 2021 and 2022.

The disappearance of *D. australis* aggregations in the Port Stephens estuary between 2021 and 2022 is of grave concern for this endangered species. Without these clusters of colonies, their ability to reproduce may be hindered. Although there is evidence that *D. australis* can asexually propagate (Larkin et al. 2023b), genetic analyses indicate that sexual reproduction is likely its primary mode of proliferation (Williamson et al. 2022), as has been found for other Malacalcyonacean species (McFadden 1997; Bastidas et al. 2001). A recent study provides evidence that *D. australis* is a gonochoric broadcast spawner (Larkin et al. 2023b). Consequently, the presence of numerous sexually mature colonies of different sexes within the same reef system may be critical to facilitate genetic diversity, adaptation, and resilience for the recovery of *D. australis* populations.

This study demonstrates that *D. australis* soft coral is on the brink of extinction in the Port Stephens estuary, which previously supported by far the largest population of the species. Surveys conducted by other researchers confirmed that small aggregations previously present in Brisbane Water (Vincent Raoult, pers comm, 2022) and in Sydney (John Turnbull, pers comm, 2022), NSW also disappeared after these flood events. However, some aggregations have started

to reestablish in Sydney (John Turnbull, pers comm, 2023). As of September 2023, the largest known aggregation of large (≥ 30 cm average diameter) and healthy colonies is located on the scuttled navy frigate ex-HMAS Adelaide, near Terrigal, NSW. With access to these remaining aggregations as a source of potential donor cuttings, investigations are currently underway to determine the feasibility of restoration using the transplantation of cuttings (Larkin et al. 2021a, 2023a). Preliminary trials using lab-based in vitro fertilisation techniques with gravid fragments also show promise for future remediation measures to help *D. australis* populations recover in the Port Stephens estuary and to ensure the species' ongoing survival in the wild (Larkin et al. 2023b).

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Data Availability Data and documentary evidence are available from the corresponding author upon reasonable request.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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References

- Adams, J.B., S. Taljaard, L. van Niekerk, and D.A. Lemley. 2020. Nutrient enrichment as a threat to the ecological resilience and

- Erftemeijer, P.L., B. Riegl, B.W. Hoeksema, and P.A. Todd. 2012. Environmental impacts of dredging and other sediment disturbances on corals: A review. *Marine Pollution Bulletin* 64: 1737–1765.
- Eyre, B., and C. Twigg. 1997. Nutrient behaviour during post-flood recovery of the Richmond River Estuary, Northern NSW, Australia. *Estuarine, Coastal and Shelf Science* 44: 311–326.
- Fabricius, K.E., A. Genin, and Y. Benayahu. 1995. Flow-dependent herbivory and growth in zooxanthellae-free soft corals. *Limnology and Oceanography* 40: 1290–1301.
- Fell, P.E., P.-A. Knight, and W. Rieders. 1989. Low-salinity tolerance of and salinity-induced dormancy in the estuarine sponge *Microciona prolifera* (Ellis et Solander) under long-term laboratory culture. *Journal of Experimental Marine Biology and Ecology* 133: 195–211.
- Finlay-Jones, H., V. Raoult, D. Harasti, and T. Gaston. 2021. What eats a cauliflower coral? An assessment of predation on the endangered temperate soft coral, *Dendronephthya australis*. *Marine and Freshwater Research* 73: 307–318.
- Freeman, L.A., D.R. Corbett, A.M. Fitzgerald, D.A. Lemley, A. Quigg, and C.N. Steppe. 2019. Impacts of urbanization and development on estuarine ecosystems and water quality. *Estuaries and Coasts* 42: 1821–1838.
- Fulton, C.J., M.N. Noble, B. Radford, C. Gallen, and D. Harasti. 2016. Microhabitat selectivity underpins regional indicators of fish abundance and replenishment. *Ecological Indicators* 70: 222–231.
- Gifford, S., H. Dunstan, W. O'Connor, and G.R. Macfarlane. 2005. Quantification of in situ nutrient and heavy metal remediation by a small pearl oyster (*Pinctada imbricata*) farm at Port Stephens, Australia. *Marine Pollution Bulletin* 50: 417–422.
- Gasby, T.M., and G. West. 2018. Dragging the chain: Quantifying continued losses of seagrasses from boat moorings. *Aquatic Conservation: Marine and Freshwater Ecosystems* 28: 383–394.
- Hacunda, J.S. 1981. Trophic relationships among demersal fishes in a coastal area of the Gulf of Maine. *Fishery Bulletin* 79: 775–788.
- Harasti, D. 2016. Declining seahorse populations linked to loss of essential marine habitats. *Marine Ecology Progress Series* 546: 173–181.
- Harasti, D., K. Martin-Smith, and W. Gladstone. 2014. Ontogenetic and sex-based differences in habitat preferences and site fidelity of White's seahorse *Hippocampus whitei*. *Journal of Fish Biology* 85: 1413–1428.
- Hart, J.D., A.D. Blackwood, and R.T. Noble. 2020. Examining coastal dynamics and recreational water quality by quantifying multiple sewage specific markers in a North Carolina estuary. *Science of the Total Environment* 747: 141124.
- He, Q., and B.R. Silliman. 2019. Climate change, human impacts, and coastal ecosystems in the Anthropocene. *Current Biology* 29: R1021–R1035.
- Hervouet, J.M. 2000. TELEMAC modelling system: An overview. *Hydrological Processes* 14: 2209–2210.
- Hopkinson, C.S., and J.J. Vallino. 1995. The relationships among man's activities in watersheds and estuaries: A model of runoff effects on patterns of estuarine community metabolism. *Estuaries* 18: 598–621.
- Jamal, E., A. Reichelt-Brushett, and K. Benkendorff. 2022. Exposure to multiple elements reduces the health of *Saccostrea glomerata*: An assessment of the Richmond River estuary, NSW, Australia. *Marine Pollution Bulletin* 184: 114177.
- Jeng, H.A.C., A.J. Englands, R.M. Bakeer, and H.B. Bradford. 2005. Impact of urban stormwater runoff on estuarine environmental quality. *Estuarine, Coastal and Shelf Science* 63: 513–526.
- Jokiel, P.L., C.L. Hunter, S. Taguchi, and L. Watarai. 1993. Ecological impact of a fresh-water "reef kill" in Kaneohe Bay, Oahu. *Hawaii Coral Reefs* 12: 177–184.
- Kaczmarzsky, L., and L.L. Richardson. 2011. Do elevated nutrients and organic carbon on Philippine reefs increase the prevalence of coral disease? *Coral Reefs* 30: 253–257.
- Laicher, D., K. Benkendorff, S. White, S. Conrad, R.L. Woodrow, P. Butcherine, and C.J. Sanders. 2022. Pesticide occurrence in an agriculturally intensive and ecologically important coastal aquatic system in Australia. *Marine Pollution Bulletin* 180: 113675.
- Larkin, M.F., D. Harasti, T.R. Davis, and S.D.A. Smith. 2021a. If you plant it, they will come: Rapid recruitment of habitat-dependent marine invertebrates to transplanted fragments of an endangered soft coral species. *Diversity* 13: 79.
- Larkin, M.F., T.R. Davis, D. Harasti, K. Benkendorff, and S.D.A. Smith. 2023a. Substantial advancement in aquaria rearing methods to assist recovery of an endangered soft coral. *Aquatic Conservation: Marine and Freshwater Ecosystems* 33: 1–14.
- Larkin, M.F., T.R. Davis, D. Harasti, G. Cadiou, D.E. Poulos, and S.D. Smith. 2021b. The rapid decline of an endangered temperate soft coral species. *Estuarine, Coastal and Shelf Science* 255: 107364.
- Larkin, M.F., T.R. Davis, D. Harasti, S.D.A. Smith, T.D. Ainsworth, and K. Benkendorff. 2023b. A glimmer of hope for an endangered temperate soft coral: The first observations of reproductive strategies and early life cycle of *Dendronephthya australis* (Octocorallia: Malacalcyonacea). *Marine Biology* 170: 146.
- Lewis, D.J., E.R. Atwill, Md.G.C. Pereira, and R. Bond. 2013. Spatial and temporal dynamics of fecal coliform and *Escherichia coli* associated with suspended solids and water within five Northern California estuaries. *Journal of Environmental Quality* 42: 229–238.
- Ling, S.D., A. Davey, S.E. Reeves, S. Gaylard, P.L. Davies, R.D. Stuart-Smith, and G.J. Edgar. 2018. Pollution signature for temperate reef biodiversity is short and simple. *Marine Pollution Bulletin* 130: 159–169.
- McClanahan, T.R., and D. Obura. 1997. Sedimentation effects on shallow coral communities in Kenya. *Journal of Experimental Marine Biology and Ecology* 209: 103–122.
- McFadden, C.S. 1997. Contributions of sexual and asexual reproduction to population structure in the clonal soft coral, *Alcyonium rudyi*. *Evolution* 51: 112–126.
- Moberg, F., M. Nyström, N. Kautsky, M. Tedengren, and P. Jarayabhand. 1997. Effects of reduced salinity on the rates of photosynthesis and respiration in the hermatypic corals *Porites lutea* and *Pocillopora damicornis*. *Marine Ecology Progress Series* 157: 53–59.
- NSW Fisheries Scientific Committee. 2021. Fisheries Scientific Committee final determination for Cauliflower Soft Coral (*Dendronephthya australis*) Industries DoP. This publication is available at: https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/12777/82/Final-determination-D.australis-.pdf. Accessed 2 Apr 2022.
- NSWDPIE. 2019. *NSW Marine LiDAR Topo-Bathy 2018 Geotif, State Government of NSW and Department of Planning, Industry and Environment*. NSW: This publication is available Accessed.
- Parada, J.M., J. Molaes, and X. Otero. 2012. Multispecies mortality patterns of commercial bivalves in relation to estuarine salinity fluctuation. *Estuaries and Coasts* 35: 132–142.
- Poulos, D.E. 2011. Unique soft coral habitat in a temperate estuary: significance to biodiversity and marine park management. Honours Ph.D. thesis, University of Technology, Sydney.
- Poulos, D.E., C. Gallen, T.R. Davis, D.J. Booth, and D. Harasti. 2016. Distribution and spatial modelling of a soft coral habitat in the Port Stephens-Great Lakes Marine Park: Implications for management. *Marine and Freshwater Research* 67: 256–265.
- Poulos, D.E., D. Harasti, C. Gallen, and D.J. Booth. 2013. Biodiversity value of a geographically restricted soft coral species within a temperate estuary. *Aquatic Conservation: Marine and Freshwater Ecosystems* 23: 838–849.
- Quaas, Z., D. Harasti, T. Gaston, M. Platell, and C.J. Fulton. 2019. Influence of habitat condition on shallow rocky reef fish community structure around islands and headlands of a temperate marine protected area. *Marine Ecology Progress Series* 626: 1–13.

- Redding, J.E., R.L. Myers-Miller, D.M. Baker, M. Fogel, L.J. Raymundo, and K. Kim. 2013. Link between sewage-derived nitrogen pollution and coral disease severity in Guam. *Marine Pollution Bulletin* 73: 57–63.
- RStudio Team. 2020. RStudio: integrated development for R. Boston, MA, USA. <http://www.rstudio.com/>. Accessed 1 Feb 2023.
- Saraswat, R., M. Kouthanker, S.R. Kurtarkar, R. Nigam, S.W.A. Naqvi, and V.N. Linshy. 2015. Effect of salinity induced pH/alkalinity changes on benthic foraminifera: A laboratory culture experiment. *Estuarine, Coastal and Shelf Science* 153: 96–107.
- Selwood, K.E., M.A. McGeoch, and R. Mac Nally. 2015. The effects of climate change and land-use change on demographic rates and population viability. *Biological Reviews* 90: 837–853.
- Sigleo, A.C., and W.E. Frick. 2007. Seasonal variations in river discharge and nutrient export to a Northeastern Pacific estuary. *Estuarine, Coastal and Shelf Science* 73: 368–378.
- Steinberg, R.K., K.A. Dafforn, T. Ainsworth, and E.L. Johnston. 2020. Know thy anemone: A review of threats to octocorals and anemones and opportunities for their restoration. *Frontiers in Marine Science* 7: 590.
- Stuart-Smith, R.D., N.S. Barrett, C.M. Crawford, S.D. Frusher, D.G. Stevenson, and G.J. Edgar. 2008. Spatial patterns in impacts of fishing on temperate rocky reefs: Are fish abundance and mean size related to proximity to fisher access points? *Journal of Experimental Marine Biology and Ecology* 365: 116–125.
- Taylor, M.D. 2019. Factors affecting spatial and temporal patterns in perfluoroalkyl acid (PFAA) concentrations in migratory aquatic species: A case study of an exploited crustacean. *Environmental Science: Processes & Impacts* 21: 1946–1956.
- Taylor, M.D., J. Beyer-Robson, D.D. Johnson, N.A. Knott, and K.C. Bowles. 2018. Bioaccumulation of perfluoroalkyl substances in exploited fish and crustaceans: Spatial trends across two estuarine systems. *Marine Pollution Bulletin* 131: 303–313.
- van Leeuwen, J., J. Awad, B. Myers, and D. Pezzaniti. 2019. Introduction to urban stormwater: A global perspective. In *Urban stormwater and flood management: Enhancing the liveability of cities*, ed. V. Jegatheesan, A. Goonetilleke, J. van Leeuwen, J. Kandasamy, D. Warner, B. Myers, M. Bhuiyan, K. Spence, and G. Parker, 1–28. Cham: Springer International Publishing.
- van Lier, J.R., D. Harasti, R. Laird, M.M. Noble, and C.J. Fulton. 2017. Importance of soft canopy structure for labrid fish communities in estuarine mesohabitats. *Marine Biology* 164: 1–11.
- Verseveldt, J., and P. Alderslade. 1982. Descriptions of types and other Alcyonacean material (Coelenterata: Octocorallia) in the Australian Museum, Sydney. *Records of the Australian Museum* 34: 619–647.
- Wainwright, D. 2011. Halifax Park/Fly Point sand accumulation study, Department., Newcastle, Australia. This publication is available at: <https://indopacificimages.com/wp-content/uploads/2021/09/Halifax-Fly-Point-Sand-Accumulation-Study.pdf>. Accessed 1 Dec 2022.
- Wernberg, T., S. Bennett, R.C. Babcock, Td. Bettignies, K. Cure, M. Depczynski, F. Dufois, J. Fromont, C.J. Fulton, R.K. Hovey, E.S. Harvey, T.H. Holmes, G.A. Kendrick, B. Radford, J. Santana-Garcon, B.J. Saunders, D.A. Smale, M.S. Thomsen, C.A. Tuckett, F. Tuya, M.A. Vanderklift, and S. Wilson. 2016. Climate-driven regime shift of a temperate marine ecosystem. *Science* 353: 169–172.
- Wetz, M.S., and D.W. Yoskowitz. 2013. An ‘extreme’ future for estuaries? Effects of extreme climatic events on estuarine water quality and ecology. *Marine Pollution Bulletin* 69: 7–18.
- Williamson, J.E., M.R. Gillings, R.J. Nevatte, D. Harasti, V. Raoult, T.M. Ghaly, A.J. Stow, T.M. Smith, and T.F. Gaston. 2022. Genetic differentiation in the threatened soft coral *Dendronephthya australis* in temperate eastern Australia. *Austral Ecology* 47: 804–817.
- Yoshioka, R.M., C.J.S. Kim, A.M. Tracy, R. Most, and C.D. Harvell. 2016. Linking sewage pollution and water quality to spatial patterns of *Porites lobata* growth anomalies in Puako, Hawaii. *Marine Pollution Bulletin* 104: 313–321.