Optimising estuarine restoration plans and long-term monitoring for fish and fisheries

2020 Annual Report to Healthy Land and Water

Lead Authors

Ben Gilby

Lucy Goodridge Gaines

Contributing Authors

Christopher Henderson

Jesse Mosman

Andrew Olds

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Executive summary

Estuaries are important coastal seascapes comprised of a diversity of coastal habitats. These habitats contribute significantly to the biodiversity and productivity of coastal systems, and so are crucial providers of ecosystem services to people. However, estuarine ecosystems are under significant threat from human activities, including habitat loss, fragmentation and degradation. As a consequence, these ecosystems require focused management, and are increasingly the target of restoration actions that have specific targets around the enhancement or restoration of fish biomass, abundance and/or diversity.

It is often broadly assumed the condition of estuarine ecosystems affects the number and type of fish congregating at any single site within coastal seascapes. Similarly, it is increasingly understood the size, shape and position of these ecosystems within coastal seascapes also modifies the fish assemblage of any specific site. However, three key gaps in the literature remain. Firstly, exactly which attributes of different coastal ecosystems contribute most towards the 'quality' of those habitats for fish remains poorly understood. For example, in mangrove forests, is it the type of mangrove tree that most regulates fish assemblages, or simply the number or size of trees that matters most? Similarly, whether and how the condition of habitats combine with their position in estuaries to modify fish assemblages remains poorly understood. For example, does a habitat in poorer condition, but in a more accessible location within an estuary support a similarly diverse fish assemblage to a habitat in poorer position but in better condition? Finally, consistencies in these patterns between years, and the drivers of variability in fish assemblages between years remains debated in the literature. For example, does a decline in water quality only affect fish assemblages at sites in poorer condition, or that are less optimally placed?

These questions are crucial to coastal management for two key reasons. Firstly, restoration programs cannot be optimised without better understanding the optimal habitat composition and positioning of ecosystems. Secondly, understanding how habitat condition, position and variability over with time (especially due to variable water quality) affects the distribution of fish is crucial in properly implementing monitoring programs for estuarine fish assemblages. This is because understanding the reasons underpinning variation in fish assemblages between sampling events is crucial in disentangling the effect of management actions from natural variability and in selecting appropriate indicator metrics and indices. Therefore, the aims of this 3 year collaborative project between USC and Healthy Land and Water are to:

1. quantify interactions between habitat condition and spatial context for fish assemblages
2. quantify habitat associations along the full extent of estuaries
3. optimise ecological restoration priorities and plans
4. quantify whether fish-habitat associations are sustained over multiple years
5. optimise metrics that describe fish-habitat association for integration into monitoring programs and report card indices

The purpose of this report is to provide an update to Healthy Land and Water and their stakeholders regarding objective one and two, as above. **We report to Healthy Land and Water and their stakeholders that objectives 1 and 2 have been successfully completed.** The remaining three objectives will be addressed in subsequent annual reports in 2021 and 2022 following additional rounds of field work.

USC successfully surveyed fish assemblages and estuarine habitat condition across 13 estuaries (Noosa River, Maroochy River, Mooloolah River, Pumicestone Passage, Caboolture River, Pine River, Brisbane River, Tingalpa Creek, Logan River, Albert River, Pimpama River, Nerang River, and Tallebudgera Creek) and 629 sites in 2021. This constituted over 300 hours of processed underwater footage and 5000 measures of habitat condition. The survey effort identified a total of 78 species of fish in estuaries in Southeast Queensland and counted a total of over 11,000 individual fish during surveys.

Our broad methodological approach was to;

1. Survey fish assemblages from the estuary mouth of each system to the most upstream EHMP estuarine monitoring point. This range represents the most extensive sampling extent ever undertaken in the USC-Healthy Land and Water partnership.
2. Survey fish assemblages congregating around patches of seagrass, salt marsh, mangroves, log snags, rocky structures and soft sediments using unbaited underwater videography for 30 minutes at each site. Fish assemblage data was extracted from these videos using the standard *MaxN* metric.
3. Survey the condition of each fish survey site by employing a diversity of ecosystem-specific metrics to scale the relative condition of sites both within estuaries and between estuaries. For example, in mangrove forests, we recorded the number and species of trees, tree diameter (at both the base and breast height), canopy height and cover, the cover of benthic algae, mud, invertebrates and woody debris and the number of mangrove pneumatophores and seedlings.
4. Undertake a series of spatial analyses in GIS, including calculating the proximity to, and area of a diversity of coastal ecosystems near each site that have previously been established as important in driving fish assemblage structure in estuaries in southeast Queensland.
5. Finally, undertake multivariate statistical analyses for each ecosystem separately to show how habitat condition and seascape context combine to modify fish assemblage structure.

Species richness was highest on log snags, followed by rocky outcrops and seagrass, and then saltmarsh, mangroves and soft sediments. Fish abundance was lowest on soft sediments, with all other habitats being not significantly different to each other. There were very few consistencies in one estuary having consistently higher or lower values for either species richness or fish abundance across ecosystems. However, Tallebudgera Creek and Mooloolah Rivers tended to be in the top 2-3 ranked estuaries for species richness, and Tallebudgera Creek and Nerang River tended to be in the top 2-3 ranked estuaries for fish abundance. Conversely, there was a tendency for Brisbane, Logan and Albert Rivers to have among the lowest fish abundance and diversity.

We found significant differences in fish assemblages among all combinations of ecosystems and estuaries sampled in 2020. In this sense, fish assemblage structure at any individual site within any individual estuary was more thoroughly explained by variation in the environmental metrics and attributes of survey sites, than the estuary in which the site was located. Overall, however, differences in fish assemblages between estuaries and ecosystems were driven by species from a diversity of both fish families and functional groups. For example, the piscivorous lutjanids Moses perch *Lutjanus russelli* and mangrove jack *Lutjanus argentimaculatus* was an important indicator of variation in fish assemblies, as was the detritivore sea mullet *Mugil cephalus*, the herbivorous kyphosid luderick *Girella tricuspidata*, and the generalist feeding sparid yellowfin bream *Acanthopagrus australis*.

In general, the composition of fish assemblages at individual sites within estuaries was explained by the spatial position of sites, and not their condition. The exceptions were mangroves, which were explained by spatial metrics and the cover of mud and algae at sites, and seagrass meadows which were explained by spatial metrics and the cover of *Zostera* at sites. Generally, fish assemblages were more abundant and diverse at locations in estuaries that had greater connectivity with structured habitats like seagrass and mangroves.

Based on these findings, we have four key conclusions and recommendations;

- Estuaries of southeast Queensland support significant fish assemblages that are diverse and contain an abundance harvestable fish. Fish abundance and diversity was relatively evenly spread across habitats and estuaries, with some key exceptions. However, assemblages differed fundamentally between estuaries and habitats. This indicates that it is attributes of individual habitats, as opposed to habitat type or the estuary in which the site is located that best predicts the abundance and diversity of fish at any individual site.
- Managing the diversity of ecosystems broadly across seascapes is crucial in maximising the abundance and diversity of fish in estuaries. Similarly, maximising the extent of key ecosystems should be a focus when management seeks to increase the abundance and diversity of fish assemblages. Broadly, a focus on habitat condition, as opposed to extent and connectance, may be a less valuable proposition.
- Surveys in 2021 will focus on further disentangling the effects of the variables we established here as important for individual habitats. Consequently, we will resurvey all sites surveyed this year, as well as all significant drivers of fish assemblages within each ecosystem. This will enable us to address objective three of the broader project; optimising ecological restoration priorities and plans.
- In 2020, we were challenged by the accuracy of existing Queensland Government habitat mapping in the upper reaches of the estuaries we sampled. For example, narrow ‘veneers’ of mangroves that occur along the verges of estuaries are not clearly identified in broader habitat map layers, but are clearly crucial in explaining the patterns we found here. USC would like to take two approaches to improve this crucial consideration in 2021. Firstly, USC will discuss with HLW whether there are better maps available for our study purposes; especially for mangroves, salt marsh and seagrass. Secondly, USC will also undertake drone mapping exercises in 2021 at locations where habitat maps are lacking or poorly defined.

Surveys in 2021 will cover the same spatial extent and estuaries as those sampled in 2020. Surveys will commence in June 2021 (again, the same as for 2020), weather permitting. The next USC annual report will be submitted in December 2021.

Introduction and Background

Estuaries provide numerous ecosystem services that are valued by people. Principle among these is the provision of fish habitats for finfish and crustacean species of commercial and recreational significance (Barbier et al. 2011). However, many estuaries globally have become degraded by human activities. Estuaries have had their shorelines hardened by human infrastructure (Heery et al. 2017), and estuarine catchments are modified by human land uses, resulting in alterations to runoff regimes, water quality and estuarine habitat condition (Halpern et al. 2008). Billions of dollars are spent each year in the hope of improving the condition of estuaries worldwide, including through targeted ecological restoration of marine ecosystems and the surrounding catchment (Elliott et al. 2007; Elliott et al. 2016; Saunders et al. 2017). However, we often do not know if this investment directly benefits estuarine fishes and the ecosystems they inhabit as optimal, long-term monitoring methods are sometimes lacking. Further, these actions are often not designed and placed appropriately using quantitative data to maximise ecological outcomes, meaning that some key benefits might be missed (Gilby et al. 2018a; Saunders et al. 2017).

The distribution and abundance of fish in coastal ecosystems is modified by the condition of estuarine habitats (i.e. complexity and composition), the context (i.e. size, shape and connectivity) of the habitat within the broader seascape, and the condition of the surrounding catchment (i.e. urbanisation, agriculture, fish passage) (Henderson et al. 2019; Nagelkerken et al. 2015; Whitfield 2017). For example, it is well established that the position of habitats in estuaries relative to other habitats (Gilby et al. 2018b) and key human disturbances (Brook et al. 2018) modify the diversity of fish assemblages, and the value of coastal fisheries. Modifications to catchments and the release of pollutants can significantly change coastal water chemistry, and this can have substantial knock-on effects for fish assemblages and fisheries values (Henderson et al. 2019). Whilst these broader-scale patterns, which affect fish at scales of kilometres to tens of kilometres, are well established, the ways in which these broader-scale variables interact with local-scale variables relating to the composition and condition of habitats remain unquantified in many settings. For example, we know that the plant composition and structural complexity of salt marshes affects the diversity and abundance of fish inhabiting them (Hollingsworth and Connolly 2006; Irlandi and Crawford 1997; Jones et al. 2020; Moussalli and Connolly 1998). However, it is often unclear whether habitat in better condition, but in less ideal positions in the estuary (i.e. poorly connected, close to human disturbances) maintains high ecological value for fish (Gilby et al. 2020; Henderson et al. 2017; Jones et al. 2020). Understanding these interactions is vital in optimising the conservation of key habitats, and in designing restoration sites that maximise ecological benefits (Gilby et al. 2019).

The number and size of ecological restoration projects is growing in marine, freshwater, and terrestrial ecosystems globally (Duarte et al. 2020; Middendorp et al. 2016; Paice et al. 2016). Ecological restoration principally aims to re-establish lost or degraded ecosystems and their functioning (Hagger et al. 2017; Stanturf et al. 2014). Restoration projects can also have important goals regarding the enhancement or re-establishment of populations of specific plants and/or animals (Gilby et al. 2018a), as well as the provision and sustainability of ecosystem services like fisheries (e.g., Dame and Libes 1993). Using quantitative data to design ecological restoration projects is likely to yield better ecological, economic, and social outcomes, be cheaper, and have lower social costs and disruptions (Bullock et al. 2011). For example, re-snagging (where trees, branches and other woody debris is installed in estuaries) is a common strategy in upper estuarine areas for enhancing fish habitat values (Angermeier and Karr 1984; Crook and Robertson 1999). Understanding the optimal size, complexity and configuration of snags, and the position in estuaries that maximise overall outcomes is therefore vital in maximising overall restoration outcomes. Establishing the relative importance of habitat and spatial attributes of remnant habitat patches in estuaries, and recreating key attributes in restoration sites therefore assists in maximising the likelihood of enhancing fish and fisheries to the greatest possible degree (Gilby et al. 2019).

There are substantial challenges in monitoring estuarine fish assemblages and in incorporating aspects of these fish assemblages into long-term monitoring programs (Desmond et al. 2002; Raposa et al. 2003). For example, studies have indicated significant temporal variations in fish assemblages (Wilson and Sheaves 2001), and discussed challenges in the repeated monitoring of fish assemblages in estuaries with unpredictable water conditions (Gladstone et al. 2012). Creating system-specific guidelines which ensure the consistent collection of reliable annual data, and identifying the ways in which these data can be most effectively summarised in usable metrics for monitoring programs is therefore an important goal. Further, more thoroughly understanding the methods required for consistent, long-term monitoring of fish assemblages in estuaries will allow for more thorough quantification of the outcomes of management interventions, including ecological restoration, and more thorough setting of quantitative management objectives (Gilby et al. 2018c).

To date, collaborative projects between Healthy Land and Water and the University of the Sunshine Coast (USC) have surveyed 22 estuaries for broad patterns in fish assemblages, and then 13 estuaries for habitat-specific patterns in fish assemblages throughout southeast Queensland. These award-winning surveys (Healthy Land and Water Science Innovation Award 2016; Elsevier Award, ECSA 2018), perhaps the most thorough and widest reaching globally, have established:

- the catchment, water quality, and habitat extent and connectivity variables that most drive fish diversity and abundance,
- the human factors that impinge most upon the structure of coastal fish assemblages and the value of coastal fisheries,
- the ways in which human modifications to estuaries affect the morphology and body condition of key fisheries targets, and;
- the concentration of key pollutants in the flesh of fisheries targets in southeast Queensland estuaries.

Given these extensive surveys, the estuaries of southeast Queensland can be considered some of the best understood systems in the world. Previous surveys were, however, restricted to the euhaline stretches (marine salinity >30 ppt) of estuaries, did not sample fish assemblages over multiple years, and did not consider fish habitats from the full extent of each estuary. Consequently, our conclusions and capacity to incorporate metrics into the HLW monitoring program were restricted by the spatial and temporal scope of the surveys. Therefore, there remain several key research questions that remain unanswered, but that would assist in further optimising management and monitoring in southeast Queensland. This project has five key, and interlinking objectives and associated research questions;

1. **Objective 1- Quantifying interactions between habitat condition and spatial context for fish assemblages**
   How does the condition (i.e. density, complexity, size) of habitats interact with their position within heterogeneous estuarine seascapes to modify coastal fish assemblages?
2. **Objective 2- Quantifying habitat associations along the full extent of estuaries**
   How do fish-habitat associations vary across the full extent of each estuary, and with the relative position of habitats in estuarine seascapes?
3. **Objective 3- Optimising ecological restoration priorities and plans**

   How can metrics relating the current-day abundance and distribution of fish be reliably translated into recommendations and priorities for ecological restoration in estuaries?

4. **Objective 4- Quantifying whether fish-habitat associations are sustained over multiple years**
   Do the habitat associations of fish assemblages sustain over multiple years, and in the face of often significantly variable water quality values?
5. **Objective 5- Optimising metrics that describe fish-habitat association for integration into monitoring programs and report card indices**
   What are the optimal fish abundance, diversity, fisheries and fish habitat metrics that can be incorporated in the Healthy Land and Water report card, and to what degree do environmental variables affect these metrics over years?

This report covers objectives 1 and 2 with subsequent objectives to be addressed in the annual reports of 2021 and 2022, per the schedule of milestones.

Methods

Field methodologies in 2020 were carried out precisely according to the methods described in the original proposal.

Study systems

Fish surveys were conducted between July and August 2020 (i.e. in winter to match with previous surveys, and periods of maximum water clarity) in 13 systems, with sites positioned from the estuary mouth to the most upstream estuarine EHMP monitoring site in each system (Table 1, Figure 1). We surveyed fish assemblages in 13 estuaries; Noosa River, Maroochy River, Mooloolah River, Pumicestone Passage, Caboolture River, Pine River, Brisbane River, Tingalpa Creek, Logan River, Albert River, Pimpama River, Nerang River, and Tallebudgera Creek (Figure 1).

These estuaries were selected under the following criteria;

- A history of being surveyed by the USC-Healthy Land and Water partnership, and so we have a good understanding of the likely factors influencing the distribution of fish in the lower estuaries of these systems (Gilby et al. 2018b; Gilby et al. 2017b; Gilby et al. 2017c; Olds et al. 2018).
- These estuaries represent the full range of Environmental conditions that characterise estuaries in south-east Queensland in estuaries throughout south-east Queensland (Gilby et al. 2017c).
- Each coastal council (Noosa, Sunshine Coast, Moreton Bay, Brisbane, Redland, Logan and Gold Coast) is represented by at least one estuary (Table 1).
- Each region within the Healthy Land and Water report card is represented by one major estuary (Table 1).

Table 1 List of study estuaries, the local council and HLW report card region in which they are located, and the approximate maximum distance to be surveyed upstream.

Estuary	Council	HLW Report Card Region	Maximum upstream survey distance#
Noosa River	Noosa Council	Noosa	27 km
Maroochy River	Sunshine Coast Council	Maroochy	20 km
Mooloolah River	Sunshine Coast Council	Mooloolah	9 km
Pumicestone Passage	Sunshine Coast Council/Moreton Bay Council	Pumicestone Catchment	34 km*
Caboolture River	Moreton Bay Council	Caboolture	20 km
Pine River	Moreton Bay Council	Pine	11 km
Brisbane River	Brisbane City Council	Brisbane	77 km
Tingalpa Creek	Redland City Council	Redland	13 km
Logan River	Logan City Council	Logan	31 km
Albert River	Logan City Council	Albert	16 km
Pimpama River	Gold Coast City Council	Pimpama-Coomera	16 km
Nerang River	Gold Coast City Council	Nerang	19 km
Tallebudgera Creek	Gold Coast City Council	Tallebudgera-Currumbin	7 km

#distance from the estuary mouth to the most upstream EHMP site, as estimated from Google Earth
*distance surveyed in Pumicestone Passage is the full north-south length of the Passage, and not an upstream distance

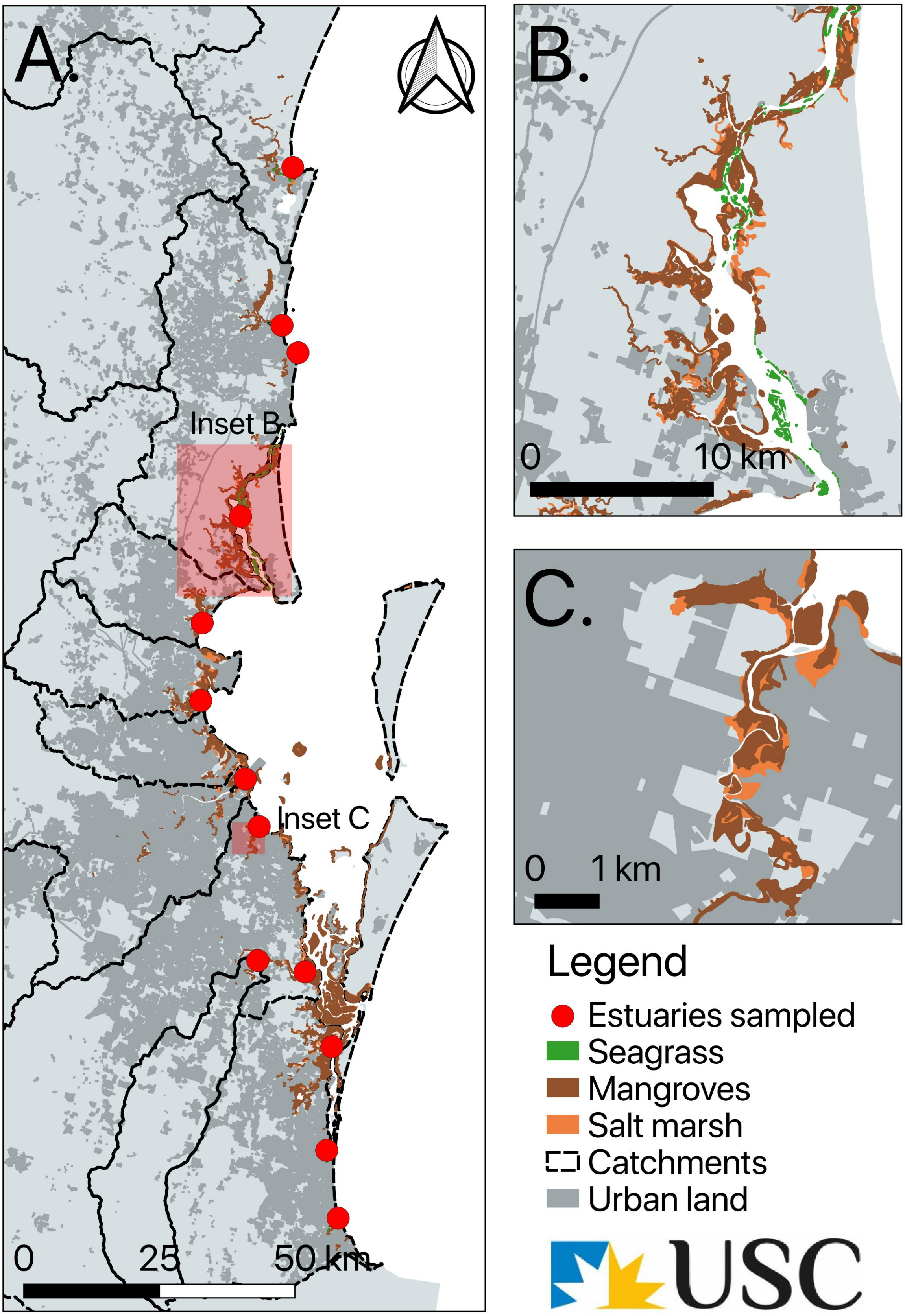


Figure 1 Map of estuaries sampled, and the key ecosystem attributes analysed in this study (i.e. seagrass, mangroves, saltmarsh and urbanisation) (A), with two insets (B and C) demonstrating the range of estuary sizes and condition sampled in this study.

Field survey methods

We used 30 minute deployments of remote underwater video stations (RUVS) to survey fish assemblages at up to 60 sites per estuary. RUVS are constructed of a GoPro camera recording in high definition, fixed to a 3kg weight and buoyed at the surface for easy retrieval and so that rope does not enter the video’s field of view. RUVS are preferred for this study to avoid the confounding effects of baited cameras drawing fishes from other habitats. Such approaches are increasingly used for the study of fishes and fish-habitat associations in coastal ecosystems (see Bradley et al. 2017; Sheaves et al. 2016). Fish assemblages were quantified from videos using the standard *MaxN* metric; the maximum number of any species observed in any single video frame.

We surveyed up to 10 replicates (depending on the extent of habitat in each system) of six key habitats in estuaries (following Gilby et al. 2018b); seagrass, mangroves, saltmarshes, log snags, rocky outcrops and soft sediment. These are the key ecosystems occurring in estuaries in southeast Queensland, are habitats that have been the focus of previous restoration efforts, and the majority were surveyed in previous iterations of the USC-Healthy Land and Water partnership (Gilby et al. 2017a). Replicates of each habitat were spread evenly across the extent of the habitat in each estuary, and from the estuary mouth to the upstream limit of sampling in each estuary (Table 1, 2, Figures 1-13). Where RUVS were placed in structured habitats (seagrass, rocky outcrops, snags, mangroves), cameras were positioned with the field of view directed obliquely along the edge of the focal habitat. Therefore, we are able to identify fishes moving in and out of the habitat, without our view being obstructed by the habitat itself.

In total, 629 camera surveys were undertaken across the six ecosystems, constituting over 300 hours of video footage, and 10,873 measurements of habitat condition were made across the region.

Table 2 The number of replicates of each ecosystem surveyed in each estuary, and the corresponding map for the position of individual sites.

Estuary	**Soft sediment**	**Log snags**	**Mangroves**	**Rocky outcrops**	**Saltmarsh**	**Seagrass**	**Grand Total**
Albert (Figure 2)	10	10	10	3	1	0	34
Brisbane (Figure 3)	8	10	10	10	2	0	40
Caboolture (Figure 4)	10	10	10	2	10	0	42
Logan (Figure 2)	10	10	10	10	10	0	50
Maroochy (Figure 5)	10	10	10	1	10	6	47
Mooloolah (Figure 6)	10	10	10	10	10	0	50
Nerang (Figure 7)	10	10	9	5	1	10	45
Noosa (Figure 8)	10	9	10	10	10	10	59
Pimpama (Figure 9)	10	10	10	3	10	5	48
Pine (Figure 10)	10	10	10	7	10	2	49
Pumicestone (Figure 11)	10	10	10	10	10	10	60
Tallebudgera (Figure 12)	10	10	10	10	10	10	60
Tingalpa (Figure 13)	10	9	10	6	10	0	45
Grand Total	128	128	129	87	104	53	629

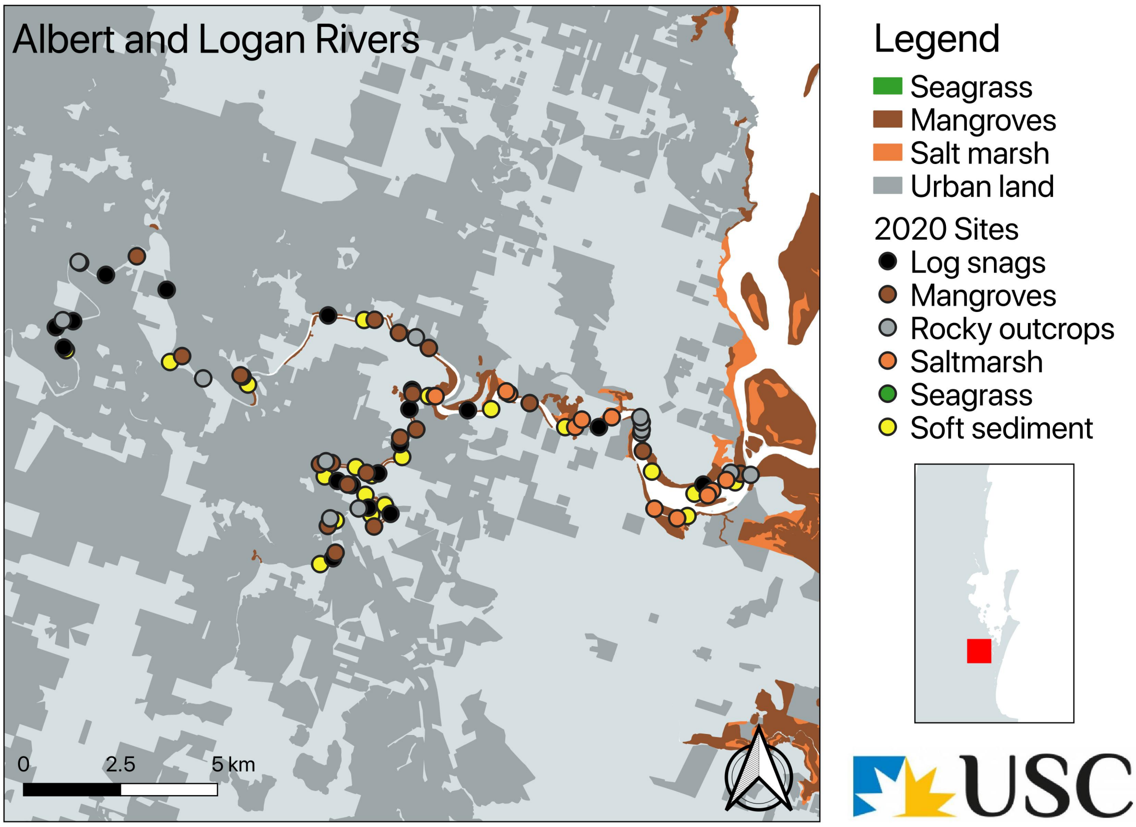


Figure 2 The distribution of sites during 2020 surveys and key features of the seascape in the Albert and Logan Rivers.

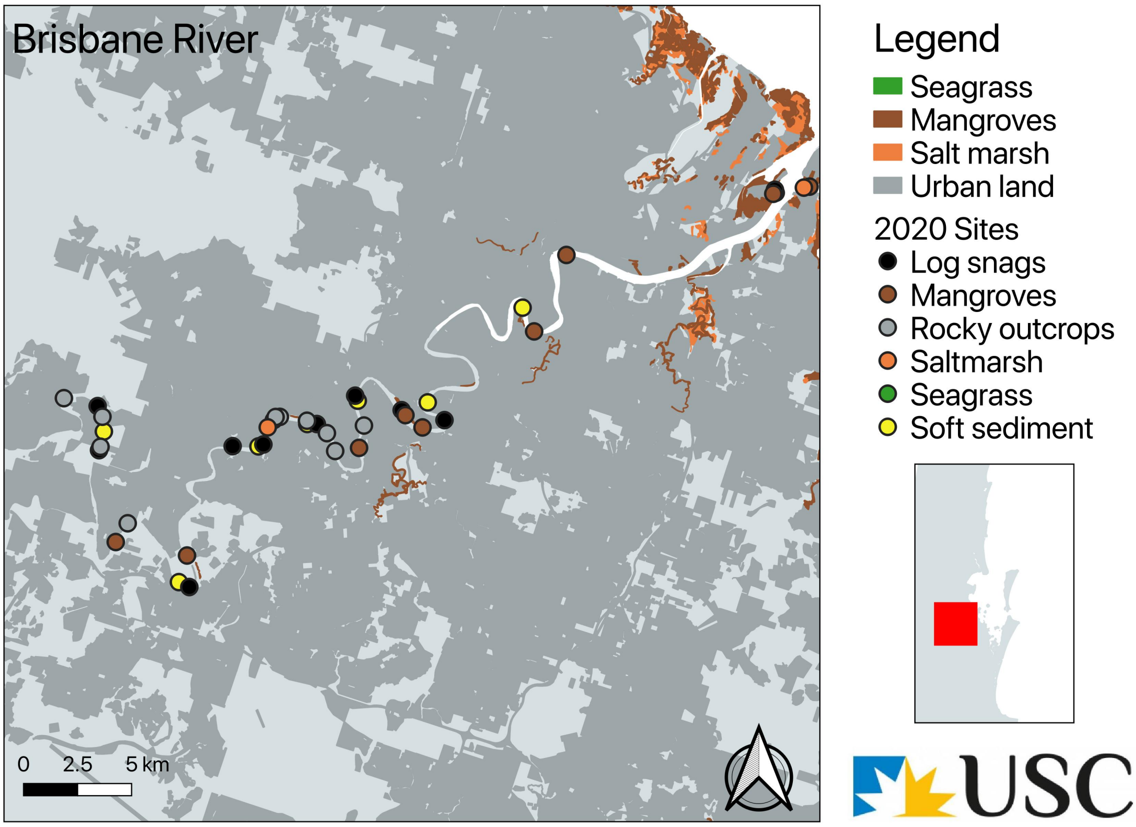


Figure 3 The distribution of sites during 2020 surveys and key features of the seascape in the Brisbane River.

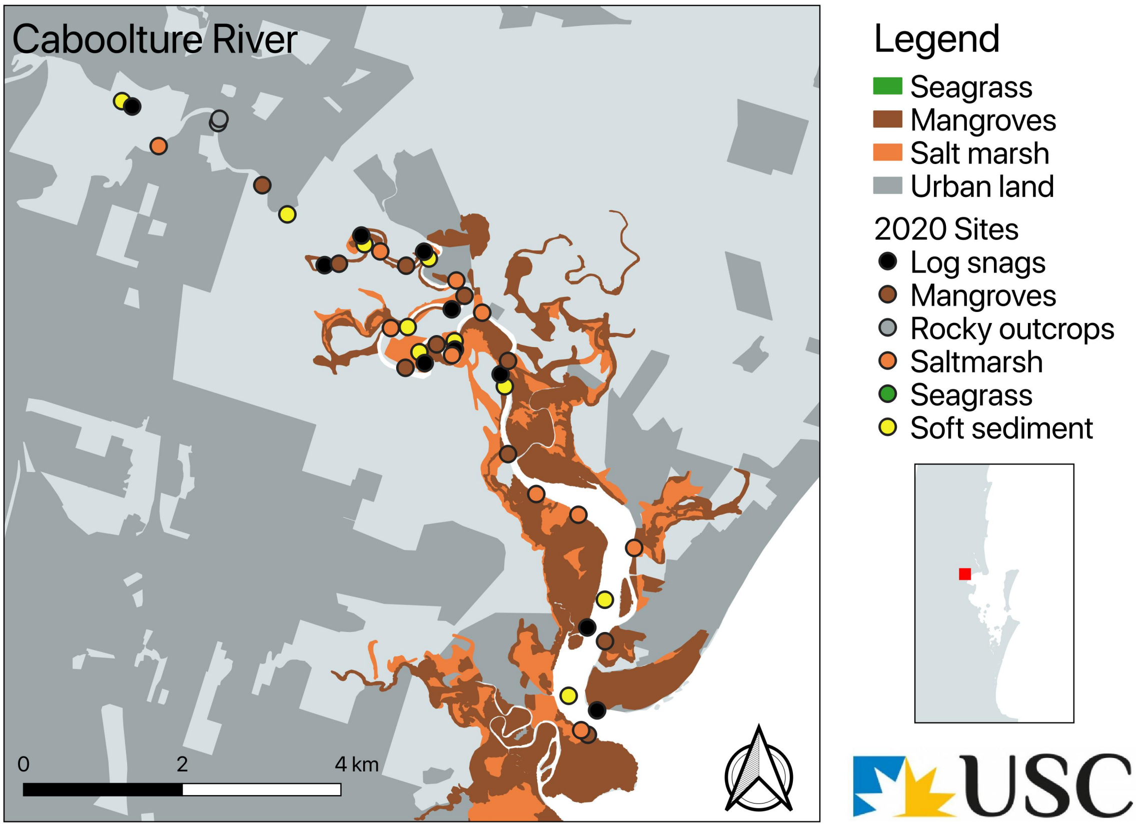


Figure 4 The distribution of sites during 2020 surveys and key features of the seascape in the Caboolture River.

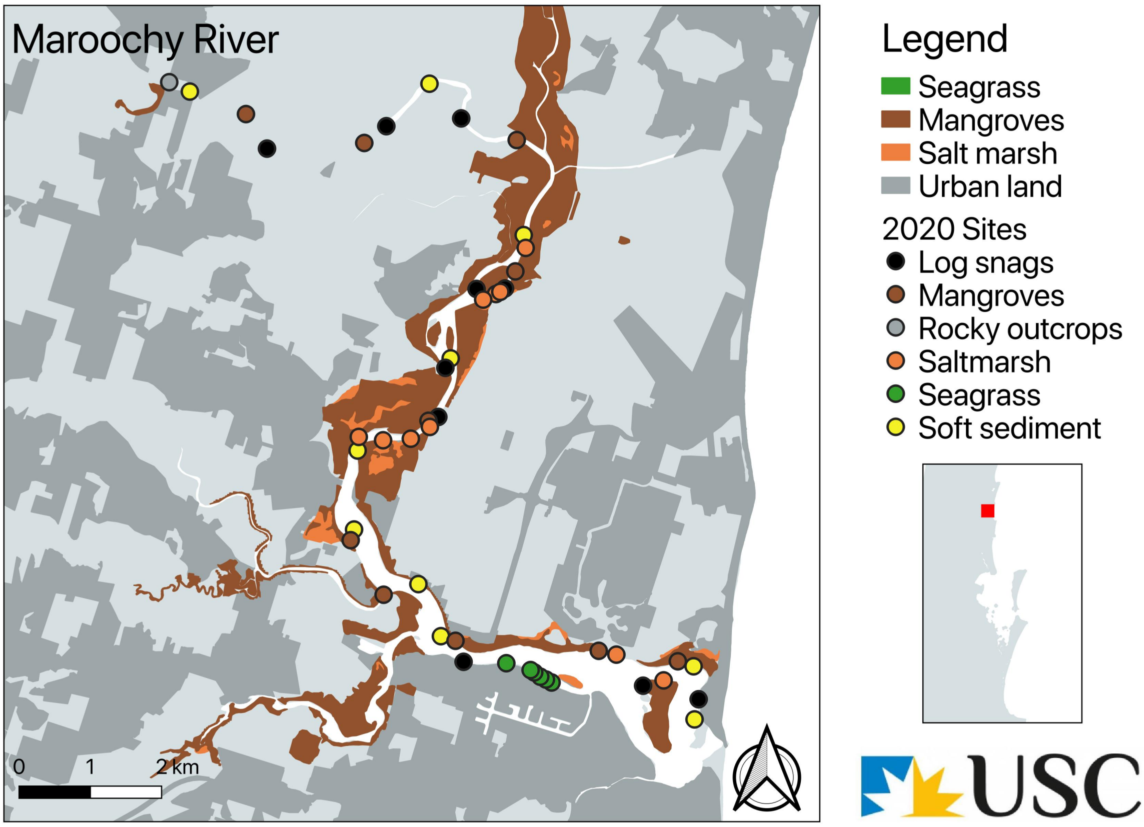


Figure 5 The distribution of sites during 2020 surveys and key features of the seascape in the Maroochy River.

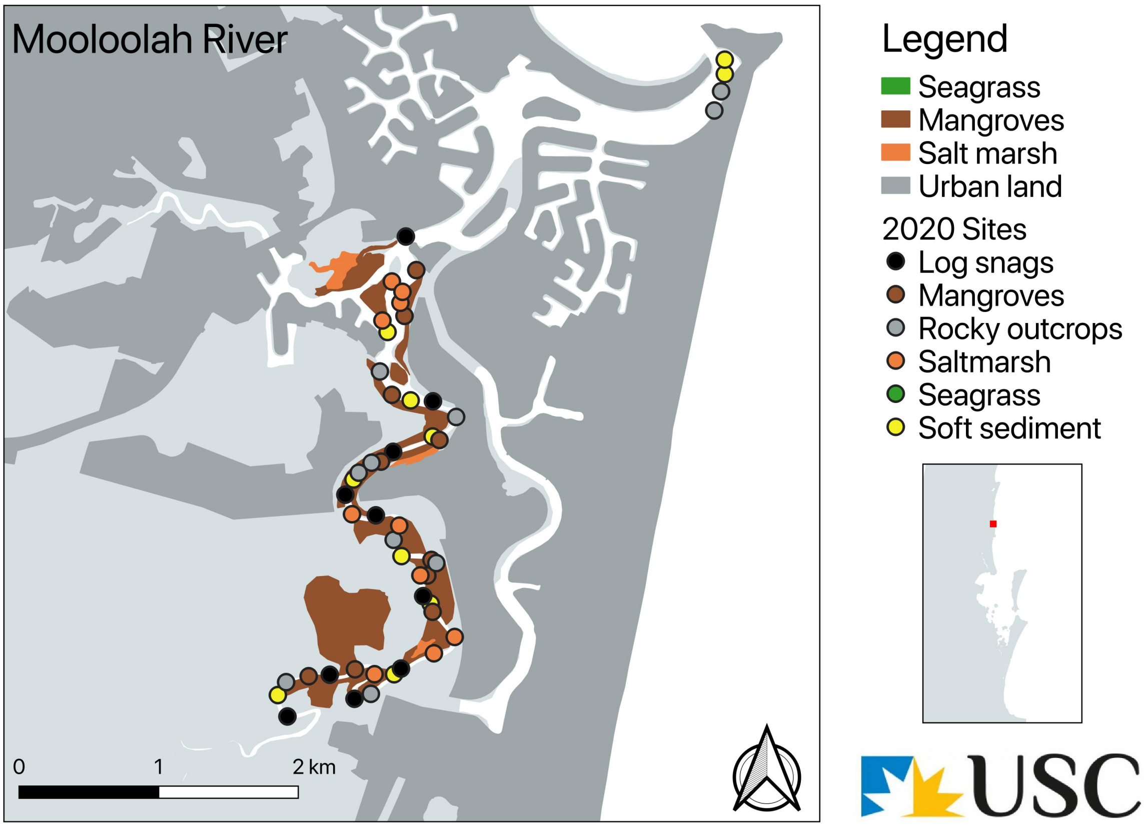


Figure 6 The distribution of sites during 2020 surveys and key features of the seascape in the Mooloolah River.

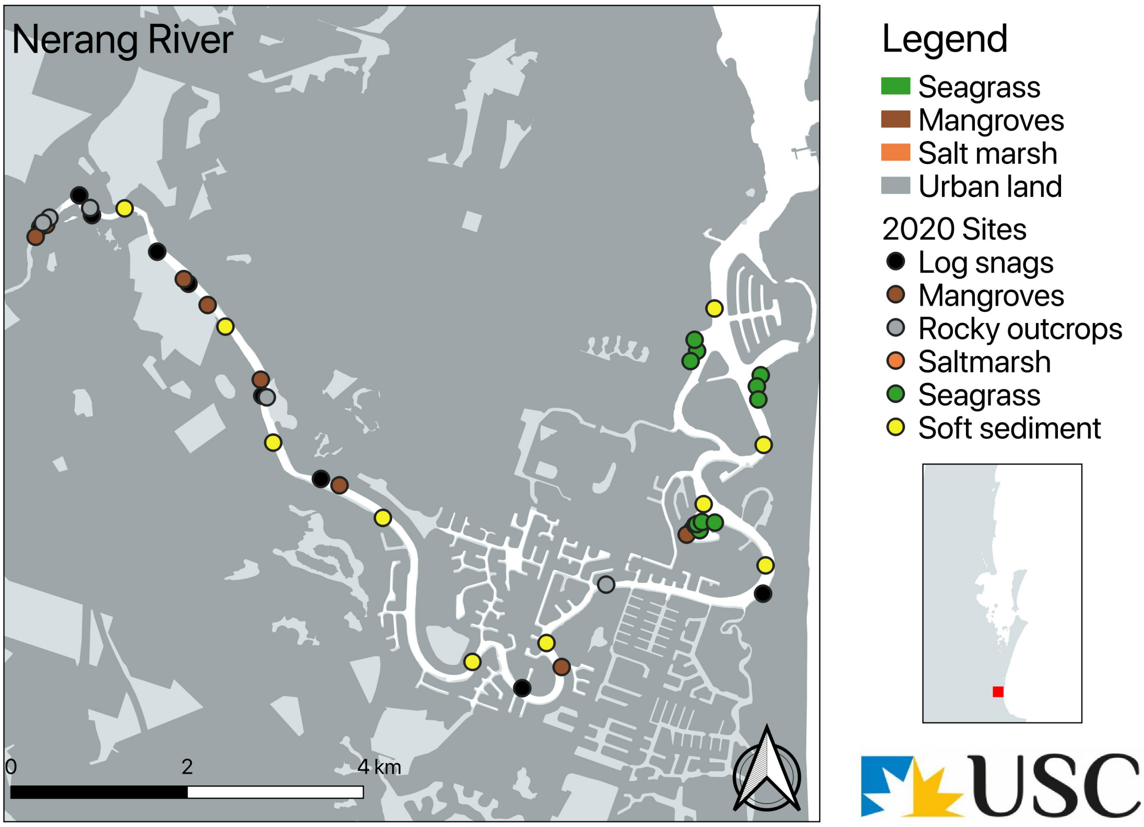


Figure 7 The distribution of sites during 2020 surveys and key features of the seascape in the Nerang River.

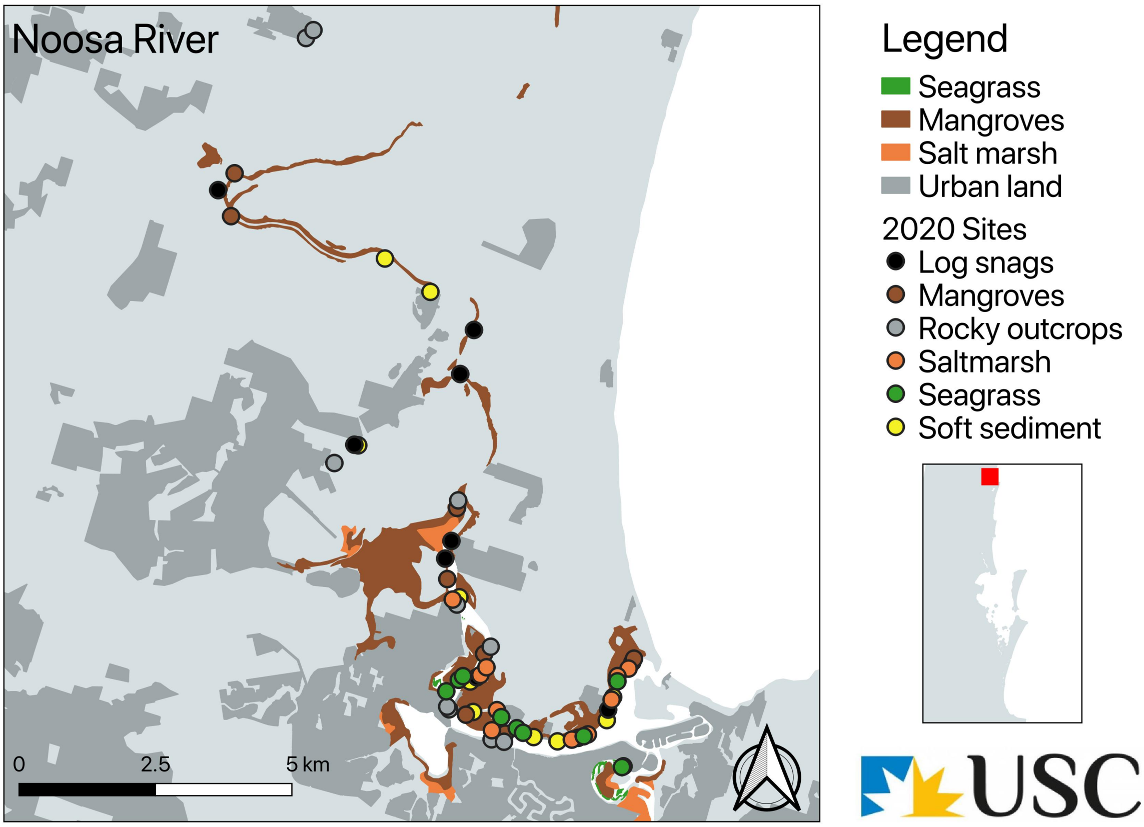


Figure 8 The distribution of sites during 2020 surveys and key features of the seascape in the Noosa River.

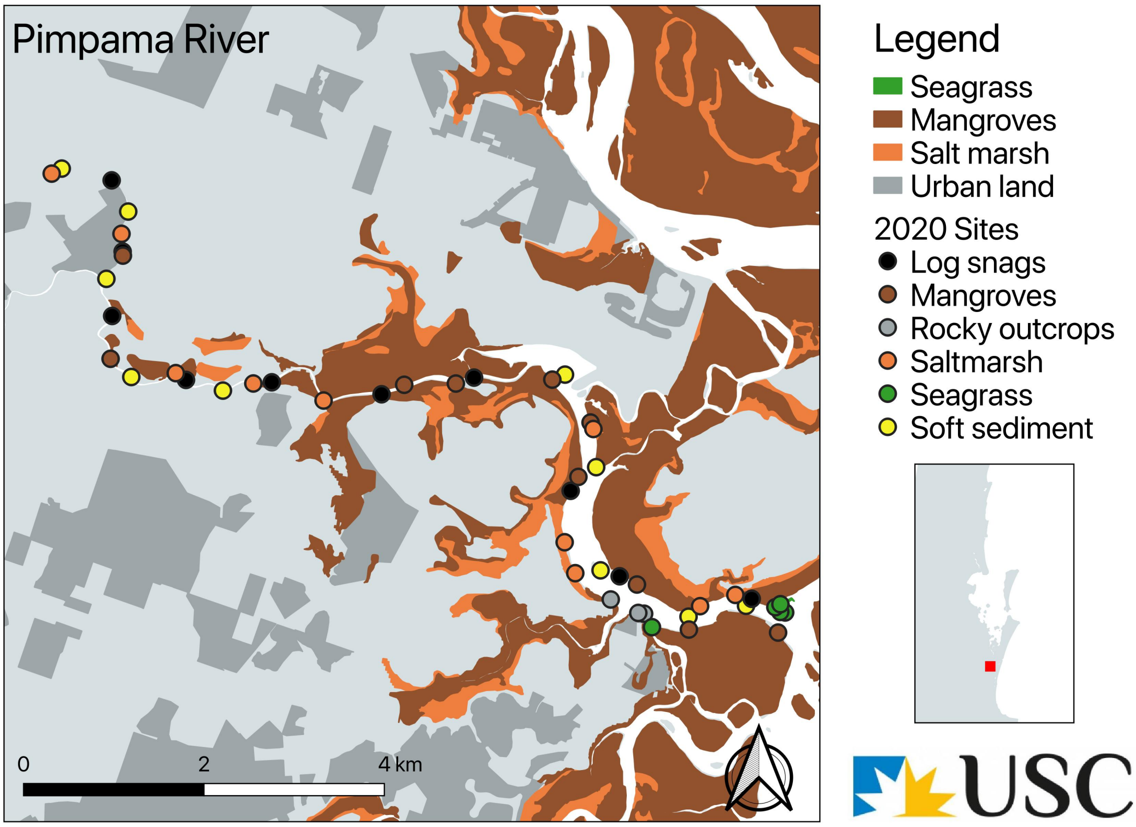


Figure 9 The distribution of sites during 2020 surveys and key features of the seascape in the Pimpama River.

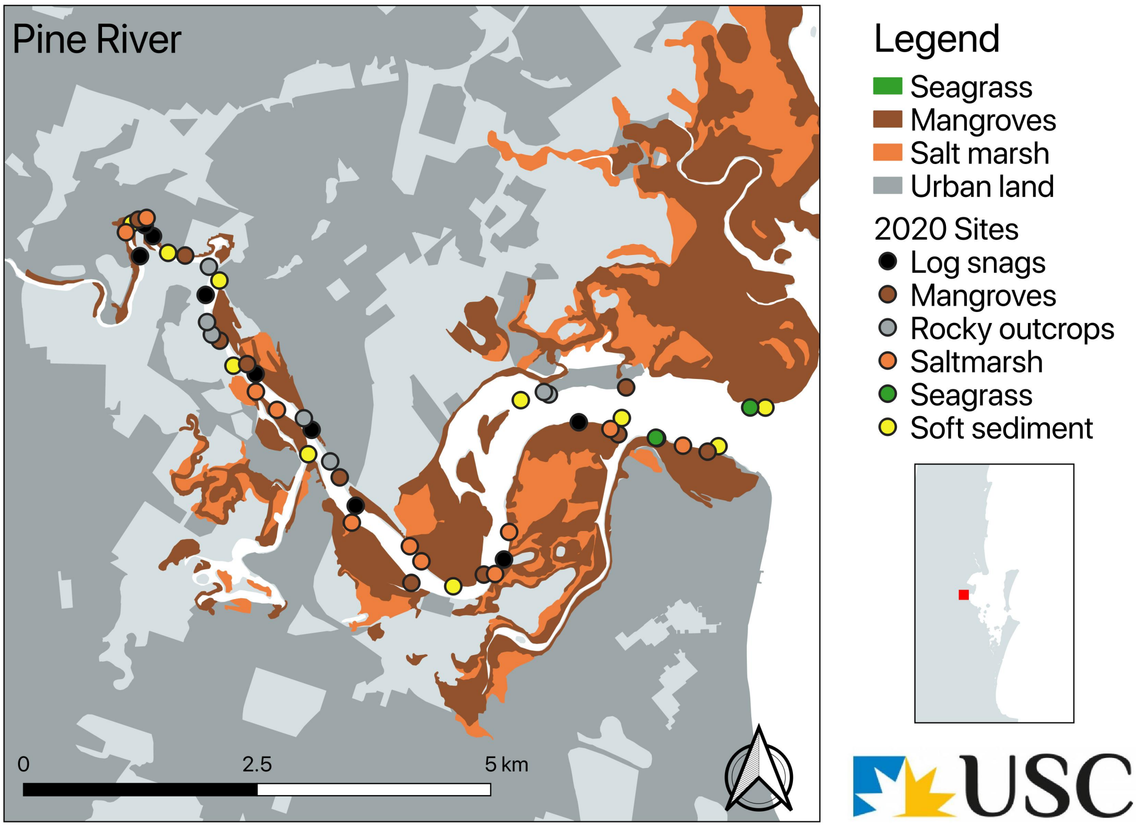


Figure 10 The distribution of sites during 2020 surveys and key features of the seascape in the Pine River.

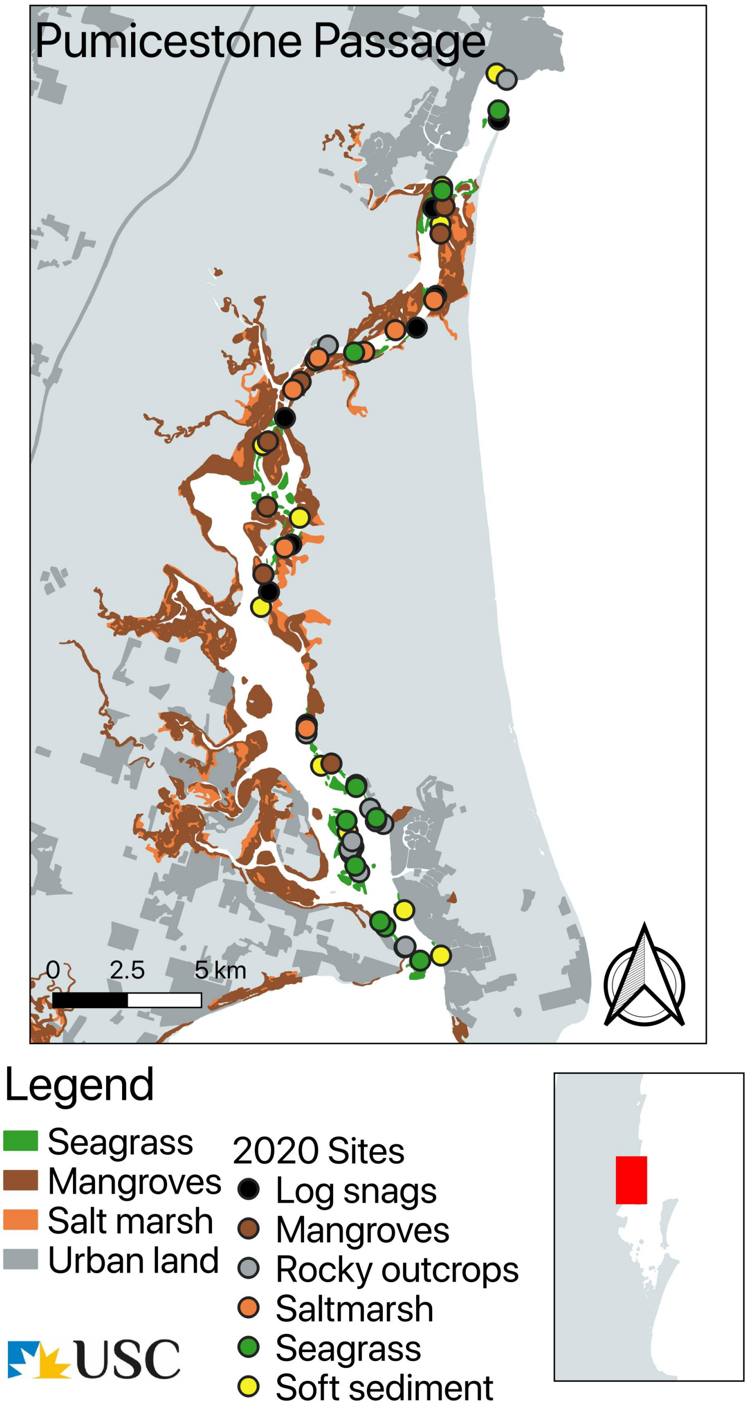


Figure 11 The distribution of sites during 2020 surveys and key features of the seascape in Pumicestone Passage.

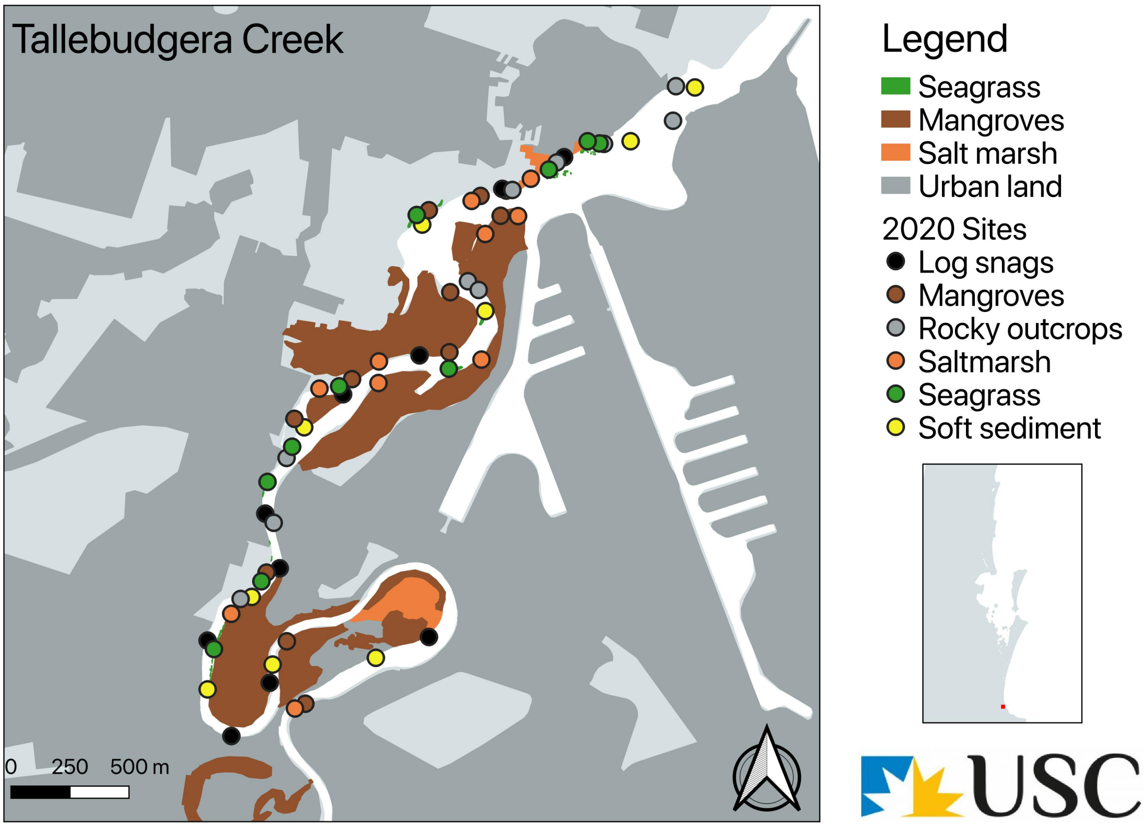


Figure 12 The distribution of sites during 2020 surveys and key features of the seascape in Tallebudgera Creek

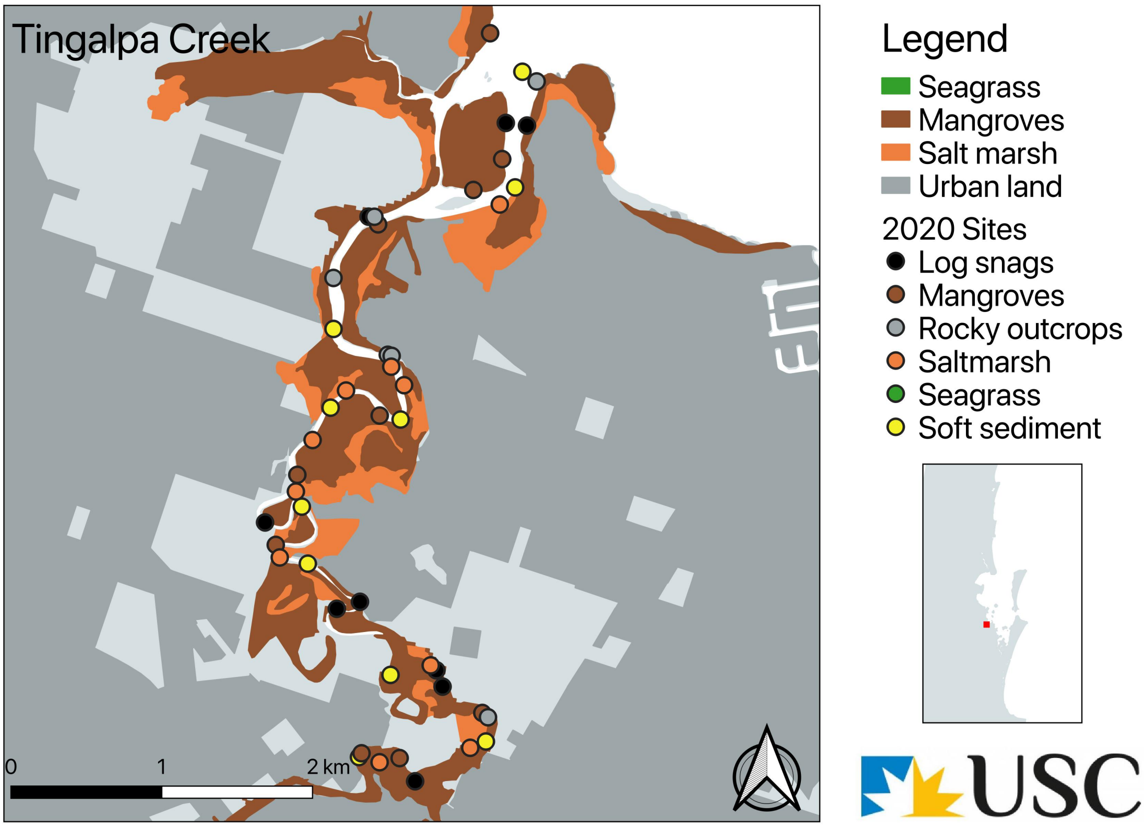


Figure 13 The distribution of sites during 2020 surveys and key features of the seascape in Tingalpa Creek.

We surveyed the ecological condition of estuarine habitats at all sites surveyed. We surveyed each ecosystem in different ways;

- Seagrass
    - We indexed the condition of seagrass meadows by recording the seagrass species composition and cover in a 10 x 10 m quadrat at the position of each camera deployment. We also measured the average shoot density and length of seagrass blades, and invertebrate density in four 50 x 50 cm quadrats placed randomly within the broader 10 x 10 m quadrat.
- Mangroves
    - We indexed the condition of mangrove forests by recording the number and species of each tree, tree diameter (at both the base and breast height) and canopy height and cover in a 10 x 10 m quadrat directly adjacent to the position of each camera deployment. We also measured the cover of benthic algae, invertebrates and woody debris and the number of mangrove pneumatophores and seedlings in four 50 x 50 cm quadrats placed randomly within the broader 10 x 10 m quadrat.
- Saltmarshes
    - We indexed the condition of saltmarshes by recording saltmarsh plant species composition, cover and height in a 10 x 10 m quadrat directly adjacent to the position of each camera deployment. We also measured plant composition, coverage and invertebrate density in four 50 x 50 cm quadrats placed randomly within the broader 10 x 10 m quadrat.
- Log snags
    - We measured the length, diameter (at four randomly chosen points on the log snag), volume, depth, complexity (on a scale from 1 being a single log, 5 being a highly complex tree with many branches), tree species (where possible) and coverage of algae and invertebrates of each log snag surveyed.
- Rocky outcrops
    - We measured the length, breadth, depth, complexity (on a scale from 1 being a single rock, 5 being many smaller rocks with complex crevices), rock type (where possible) and coverage of algae and invertebrates of each rocky outcrop surveyed.
- Soft sediment
    - We measured the composition and complexity (e.g. grain size) of soft sediment substrates by using a marine grab at each soft sediment site.

Statistical analyses

We visualised differences in fish assemblages between ecosystems and estuaries using non-metric multidimensional scaling (nMDS) ordinations calculated on fourth root transformed Bray Curtis measures. We visualised differences in habitat condition metrics between ecosystems and estuaries using nMDS ordinations calculated on normalised Euclidean distance measures. For vegetated habitats (i.e. seagrass, mangroves and salt marsh) we only analysed species whose cover was greater that 1% of total coverage.

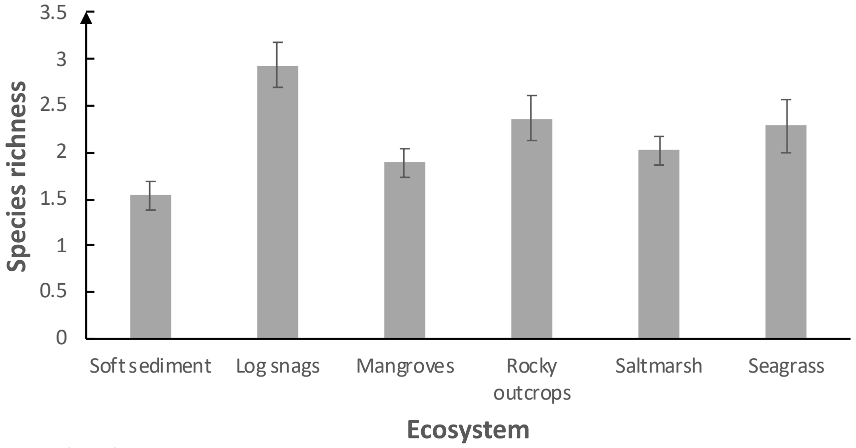
Variables which most influence the composition of fish assemblages at each ecosystem were identified using ManyGLM in the *mvabund* (Wang et al. 2012) package of the R statistical framework (R Core Team 2020). Best-fit ManyGLMs were identified using reverse stepwise simplification. Best fit variables were plotted in ordination space for each ecosystem, and the trajectory of relationships between individual species and variables from the best fit ManyGLM visualised using generalised linear latent variables models in the *gllvm* package (Niku et al. 2019) of R.

2020 Results

Fish assemblage structure and attributes
We identified 78 species during 2020 surveys. Species richness was highest on log snags, followed by rocky outcrops and seagrass, and then saltmarsh, mangroves and soft sediments (Figure 14A). We identified 11,651 individual fish on videos. Fish abundance was lowest on soft sediments, with all other habitat being not significantly different to each other (Figure 14B).

We found a significant interaction between estuary and ecosystem type for both species richness and fish abundance across the entire region (P<0.001). Here, there were very few consistencies in one estuary having regularly higher or lower values for either species richness or fish abundance across ecosystems (Figures 15,16). However, Tallebudgera Creek and Mooloolah Rivers tended to be in the top 2-3 ranked estuaries for species richness, and Tallebudgera Creek and Nerang River tended to be in the top 2-3 ranked estuaries for fish abundance. Conversely, there was a tendency for Brisbane, Logan and Albert Rivers to have among the lowest fish abundance and diversity. This supports the notion that attributes of individual sites and estuaries drive the abundance and diversity of fish assemblages, and that there is no one attribute of individual systems that consistently maximises these metrics.

A. Species richness



B. Fish abundance

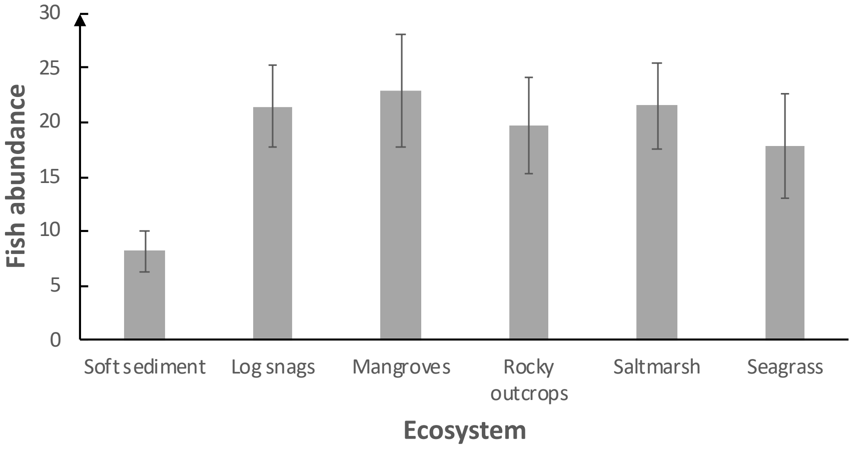


Figure 14 Average (+/- SE) of A) species richness and B) fish abundance among the ecosystems surveyed.

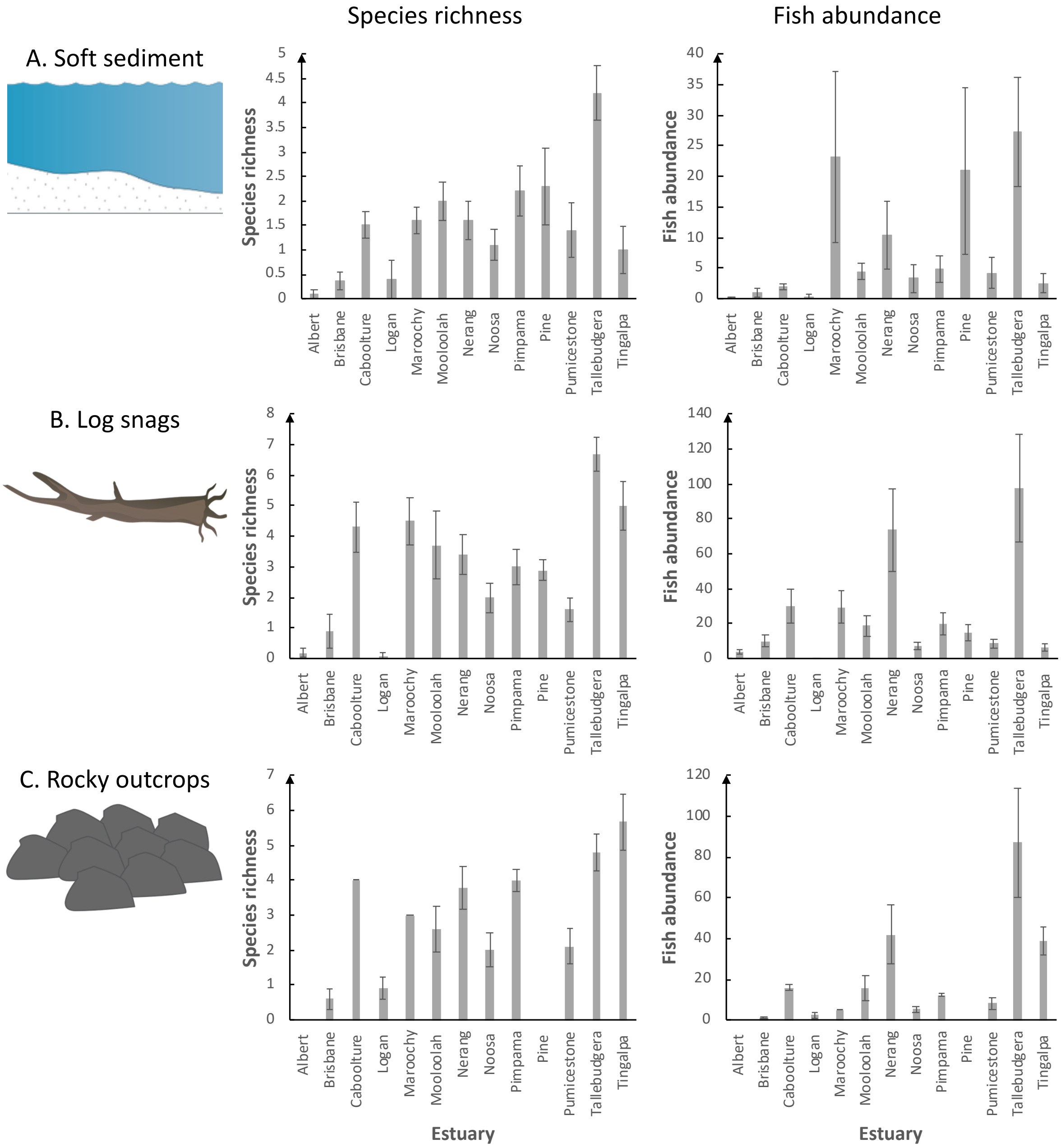


Figure 15 Average (+/- SE) species richness (left column) and fish abundance (right column) for A) soft sediments, B) log snags, and C) rocky outcrops for the estuaries surveyed.

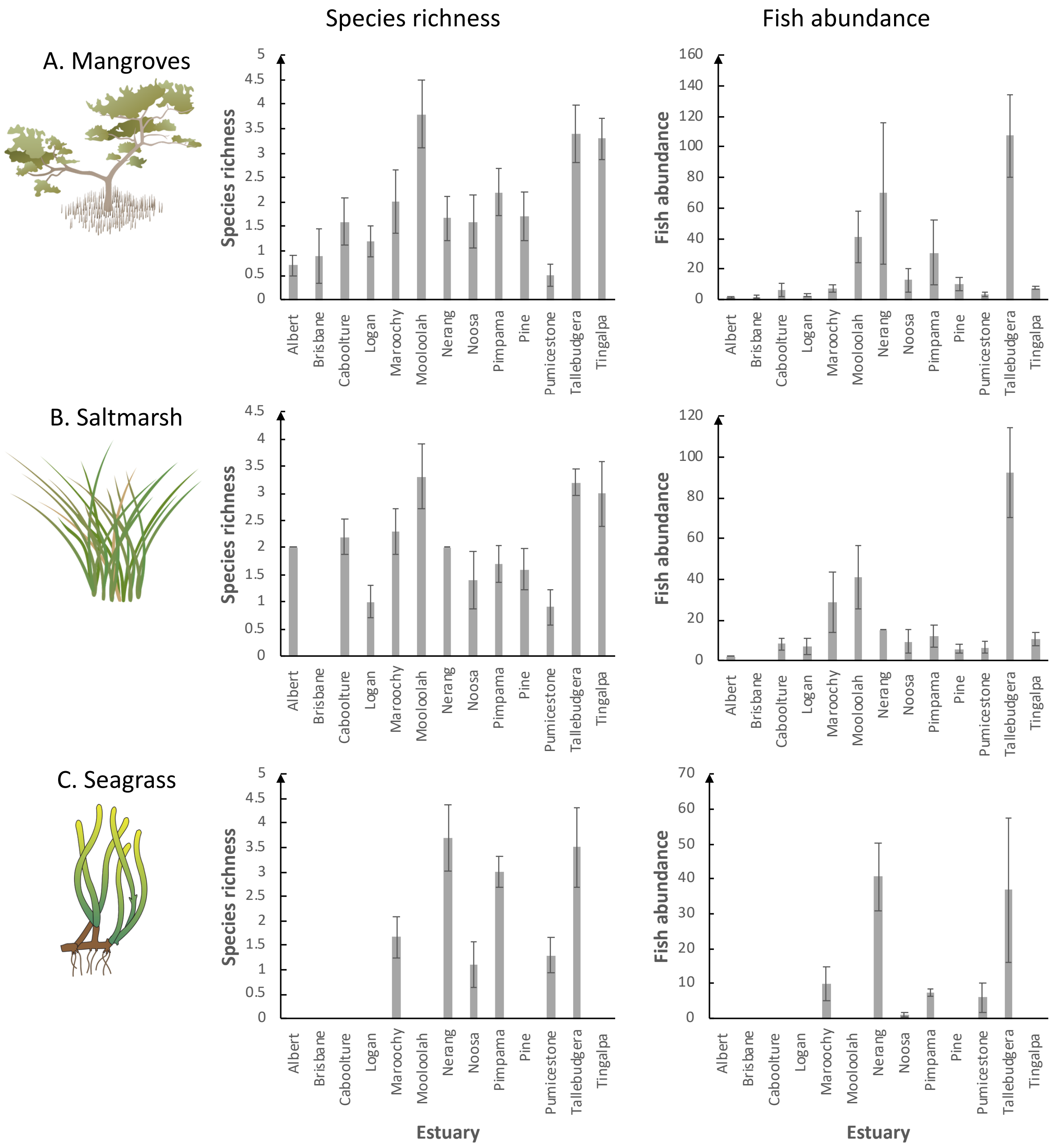
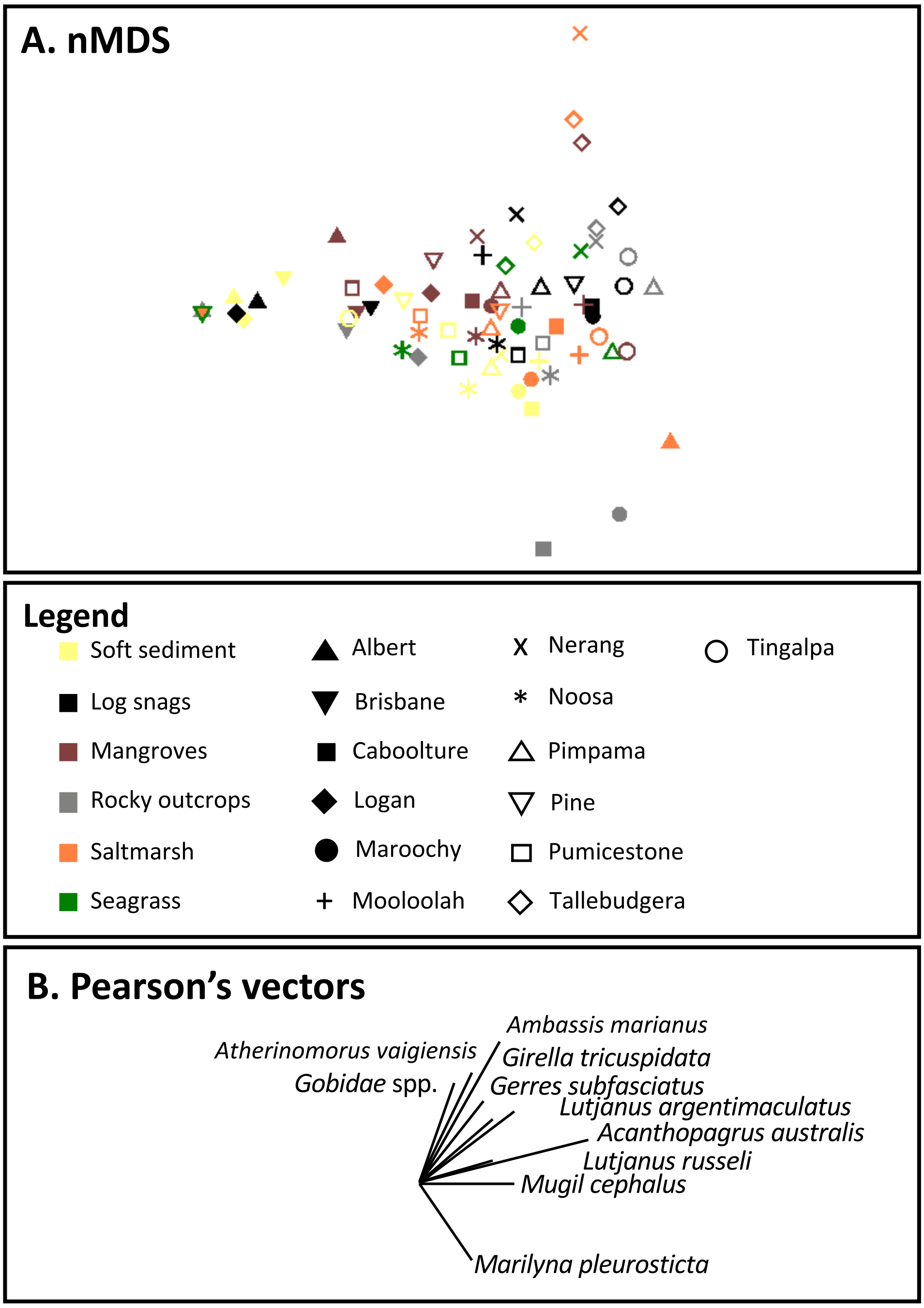


Figure 16 Average (+/- SE) species richness (left column) and fish abundance (right column) for A) mangroves, B) saltmarsh, and C) seagrass for the estuaries surveyed.

These findings were further supported by nMDS ordinations of centroid values for all ecosystem-estuary combinations (Figure 17). Here, there were no consistent patterns in any estuary or ecosystem having consistently different fish assemblages. Overall, however, fish differences in fish assemblages were driven by species from a diversity of both fish families and functional groups. For example, the piscivorous lutjanids Moses perch *Lutjanus russelli* and mangrove jack *Lutjanus argentimaculatus* was an important indicator of variation in fish assemblies, as was the detritivore sea mullet *Mugil cephalus*, the herbivorous kyphosid luderick *Girella tricuspidata*, and the generalist feeding sparid yellowfin bream *Acanthopagrus australis* (Figure 17).


A. nMDS

B. Pearson's vectors

Figure 17 Non-metric multidimensional scaling (nMDS) ordination of fish assemblages (A) with Pearson's vector overlays (B) of centroid values for each ecosystem and estuary. Here, the nearer two points are, the more similar their average assemblage is, and vice versa. Pearson's vectors indicate the direction in which each species is both most abundance and prevalent, with the length of the vector indicating the strength of the relationship.

Estuarine habitat structure and attributes

Log snag diameter and cover of barnacles was highest in the Pine River and Tallebudgera Creek, and lowest in Tingalpa Creek and Pimpama River (Figure 18). Conversely, the Brisbane and Albert Rivers were characterised by larger and more complex log snags, with greater algae cover. Conversely, low complexity and small volume log snags were more prevalent in the Maroochy, Nerang, Mooloolah and Pimpama Rivers (Figure 18).

Oyster coverage on rocky outcrops was highest in Pumicestone Passage and Tallebudgera Creek, and lowest in Tingalpa Creek (Figure 19). Algae cover on rocky outcrops was highest in the Noosa, Nerang and Albert Rivers, and lowest in the Logan, Caboolture and Maroochy Rivers (Figure 19). Finally, rocky outcrops in Tingalpa Creek and Pine River had greatest volume, complexity, and barnacle cover, and these attributes were lowest in Pimpama River, Pumicestone Passage and Tallebudgera Creek (Figure 19).

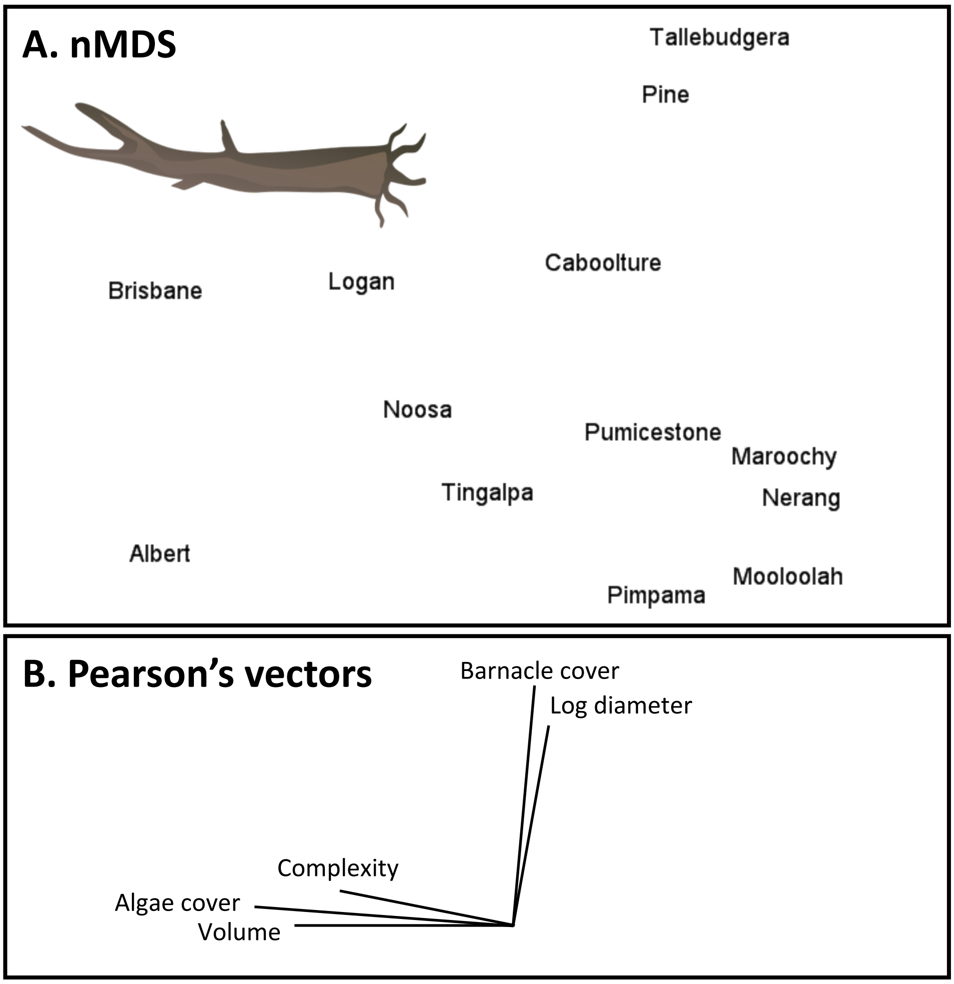


Figure 18 Non-metric multidimensional scaling (nMDS) ordination of attributes of log snags (A) with Pearson's vector overlays (B) of centroid values for each estuary. Here, the nearer two estuaries are, the more similar their average attributes of log snags are, and vice versa. Pearson's vectors indicate the direction in which each variable is greatest, with the length of the vector indicating the strength of the relationship.

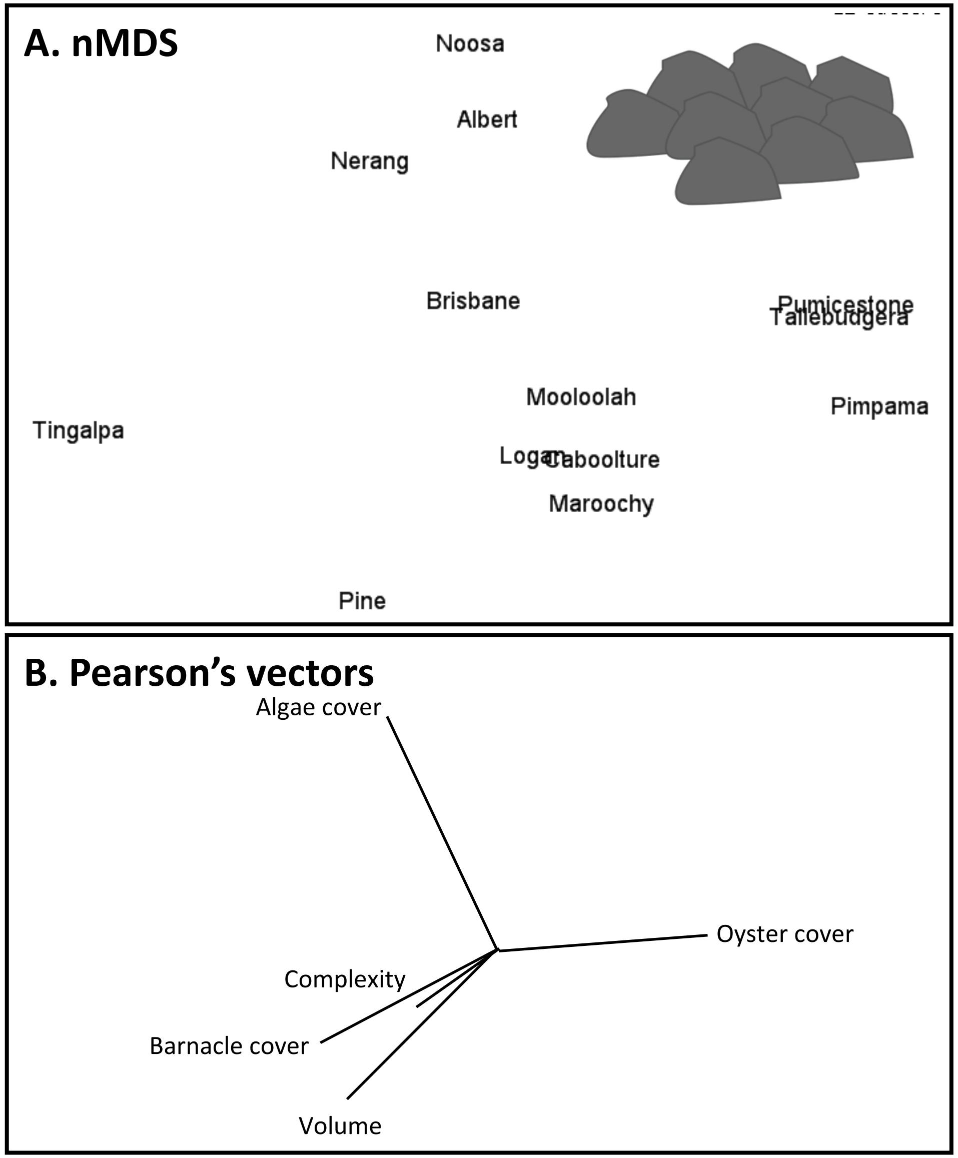


Figure 19 Non-metric multidimensional scaling (nMDS) ordination of attributes of rocky outcrops (A) with Pearson's vector overlays (B) of centroid values for each estuary. Here, the nearer two estuaries are, the more similar their average attributes of rocky outcrops are, and vice versa. Pearson's vectors indicate the direction in which each variable is greatest, with the length of the vector indicating the strength of the relationship.

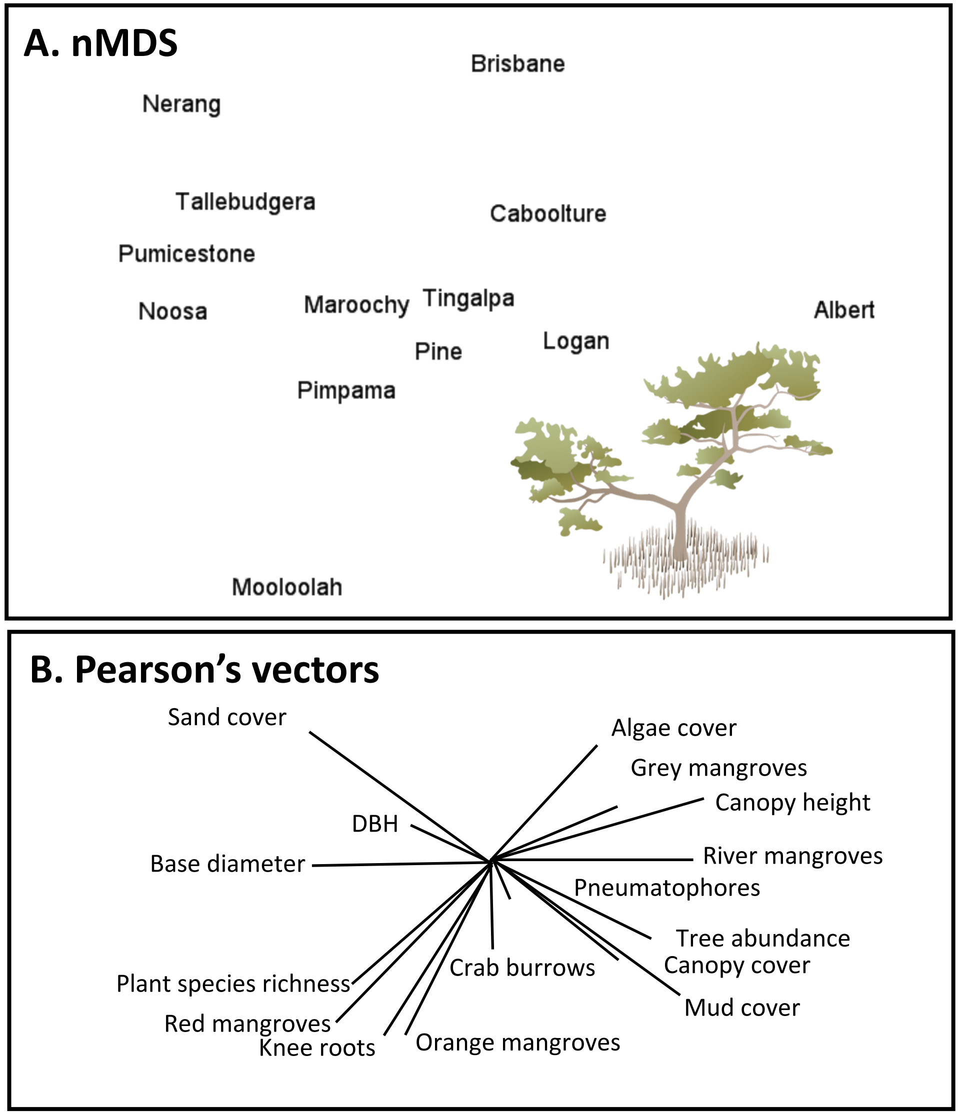


Figure 20 Non-metric multidimensional scaling (nMDS) ordination of attributes of mangroves (A) with Pearson's vector overlays (B) of centroid values for each estuary. Here, the nearer two estuaries are, the more similar their average attributes of mangroves are, and vice versa. Pearson's vectors indicate the direction in which each variable is greatest, with the length of the vector indicating the strength of the relationship.

Mangrove forests in the Albert River were classified by high tree abundance, and canopy and mud cover and low sand cover and tree diameter at breast and base height, whereas mangrove forests in Nerang River and Tallebudgera Creek had the opposite patterns (Figure 20). Mangrove forests in the Mooloolah, Pimpama, Pine and Noosa Rivers were classified by higher plant species richness, higher abundance of red and orange mangroves and knee root, and lower algae cover, canopy height and grey mangrove abundance. Conversely, mangrove forests in the Caboolture and Brisbane Rivers had lower plant species richness, lower abundance of red and orange mangroves and knee root, and higher algae cover, canopy height and grey mangrove abundance (Figure 20).

Salt marshes in the Brisbane and Albert Rivers were classified as having high plant species richness and plant height, and low salt couch coverage (Figure 21A). All others had fairly similar salt marsh conditions (Figure 21A). Within this group of estuaries, however, the Logan, Pine and Caboolture Rivers were classified by greater coverage of salt couch, bead weed and seablite, and greater species richness, and lower sand coverage. Conversely, Tallebudgera Creek and Nerang River were characterised by the opposite patterns (Figure 21B,C). Salt marshes in Maroochy River and Pumicestone Passage were characterised by higher density of crab burrows, and lower plant height (Figure 21B,C).

Seagrass meadows in Pumicestone Passage were characterised by high *Zostera* and *Halophila ovalis* coverage, high shoot density, and low sand cover, where sea grass meadows in the Pine River were characterised by low *Zostera* and *Halophila ovalis* coverage, low shoot density, and high sand cover (Figure 22A). All other had fairly similar salt marsh conditions (Figure 22A). Within this group of estuaries, however, seagrass meadows in Maroochy and Noosa Rivers were characterised by high *Zostera* cover, and low shoot density and *Halophila ovalis* cover (Figure 22B,C), while Pimpama and Nerang Rivers were characterised by low *Zostera* cover, and high shoot density and *Halophila ovalis* cover (Figure 22B,C).

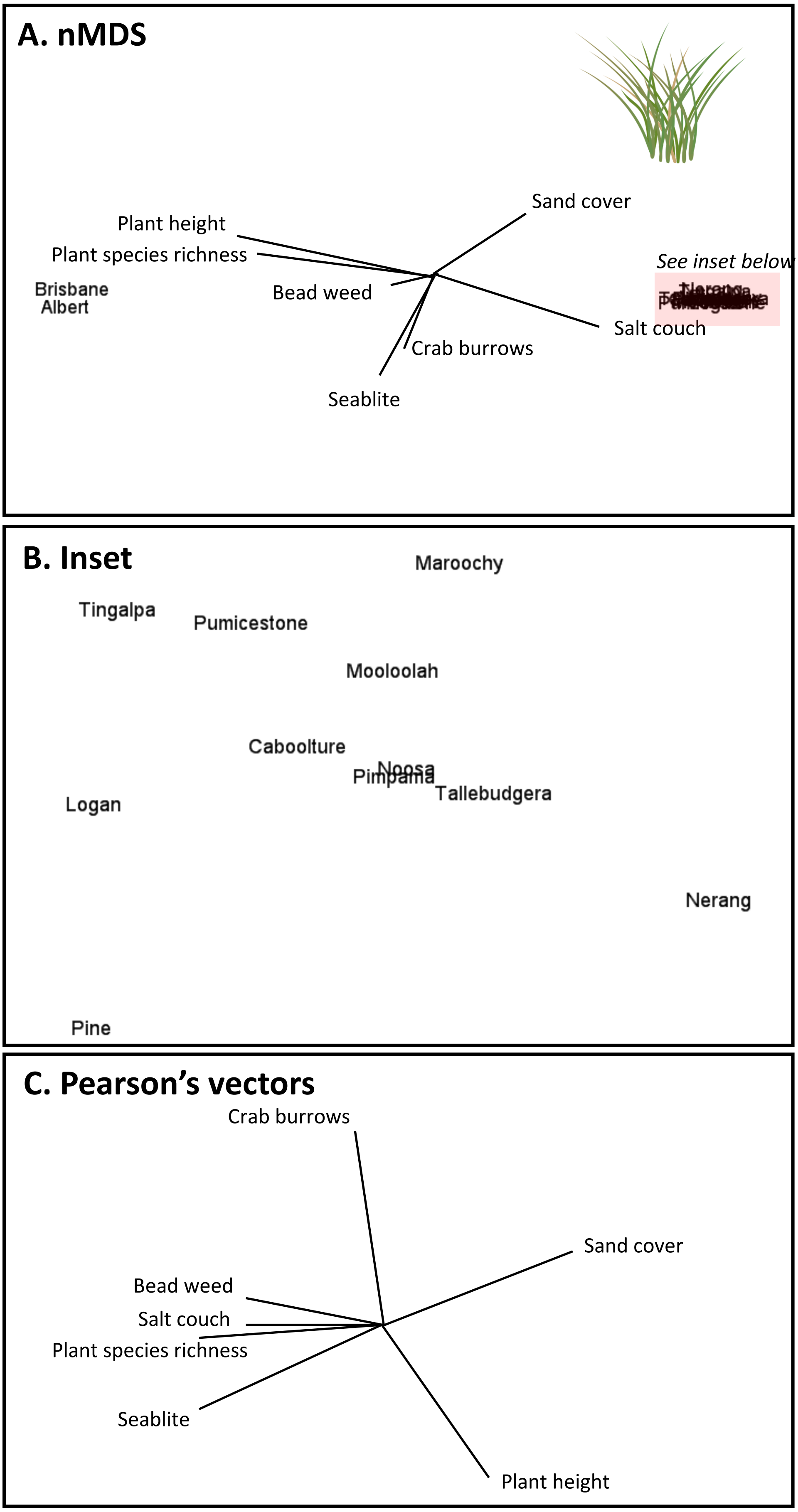


Figure 21 Non-metric multidimensional scaling (nMDS) ordination of attributes of salt marsh with Pearson's vector overlays (A), and an inset to highlight similar estuaries (B) with associated Pearson's vector overlays (C) of centroid values for each estuary. Here, the nearer two estuaries are, the more similar their average attributes of salt marsh are, and vice versa. Pearson's vectors indicate the direction in which each variable is greatest, with the length of the vector indicating the strength of the relationship.

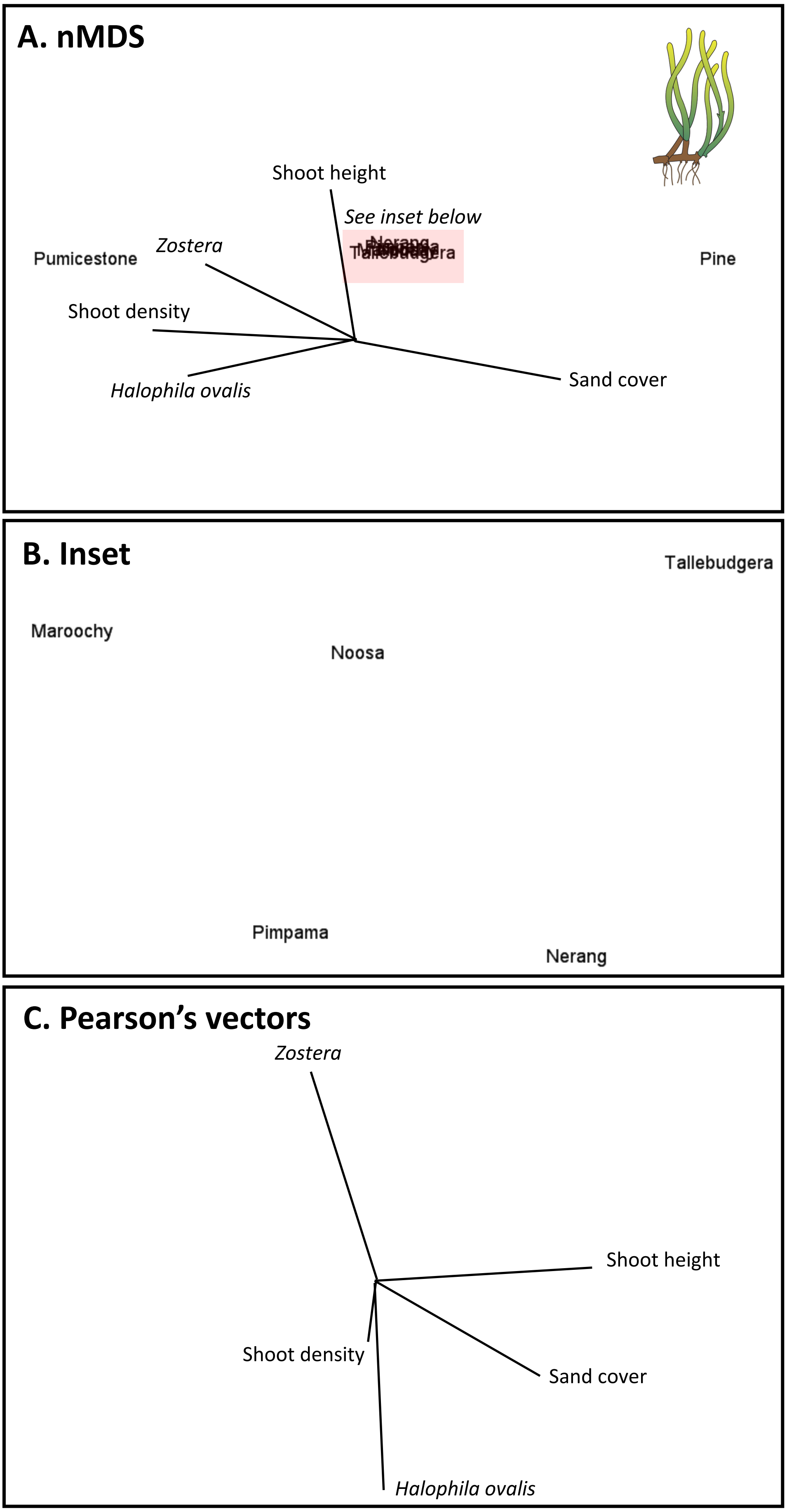


Figure 22 Non-metric multidimensional scaling (nMDS) ordination of attributes of seagrass with Pearson's vector overlays (A), and an inset to highlight similar estuaries (B) with associated Pearson's vector overlays (C) of centroid values for each estuary. Here, the nearer two estuaries are, the more similar their average attributes of seagrass are, and vice versa. Pearson's vectors indicate the direction in which each variable is greatest, with the length of the vector indicating the strength of the relationship.

Relationships between fish assemblages and habitat condition and position

We found few consistencies in the variables driving fish assemblages within each ecosystem (Table 3). We did, however, find that fish assemblages were most often explained by variation in spatial metrics than metrics that index the condition of habitats. The exceptions were mangroves, which were explained by spatial metrics and the cover of mud and algae at sites, and seagrass meadows which were explained by spatial metrics and the cover of *Zostera* at sites (Table 3).

Fish assemblages in soft sediment ecosystems were best explained by the proximity of the site to the ocean and the water depth of the site (Table 3). Six of the top ten indicator species in soft sediment ecosystems shared similar relationships with variables from the best fit ManyGLM. Here, sea mullet *Mugil cephalus*, estuary perchlet *Ambassis marianus* and blue catfish *Neoarius graffei* each occurred most often and in highest abundance at bare sediment sites with fundamentally different attributes (Figure 23A). Overall, the majority of fish species were in higher abundance at sites nearer to the estuary mouth and in shallower water depths (Figure 23B).

Fish assemblages on log snags were best explained by the proximity of the site to the ocean and salt marsh, and the area of intertidal flats within 500m of each site (Table 3). Five of the top ten indicator species shared similar relationships variables from the best fit ManyGLM. However, Mugilidae spp had fundamentally different preferences in terms of the position of log snags to estuary perchlet, and big eye trevally *Caranx sexfasciatus* (Figure 24A). Most species were more abundant at log snags with less intertidal area within 500m, and greater proximity to both saltmarshes and the ocean (Figure 24B).

Fish assemblages on rocky outcrops were best explained by the proximity of sites to the ocean, mangroves and urban shorelines (Table 3). Seven of the top 10 indicator species shared similar relationships variables from the best fit ManyGLM. However, striped scat *Selenotoca multifasciata* and estuary perchlet had fundamentally different preferences in terms of the position of rocky outcrops to black rabbitfish *Siganus fuscescens* (Figure 25A). Most species were more abundant at log snags nearer to mangroves and the ocean (Figure 24B). Conversely approximately 50% of species were in higher abundance at sites nearer to urban shorelines, and the other 50% were in higher abundance at sites further from urban shorelines (Figure 24B).

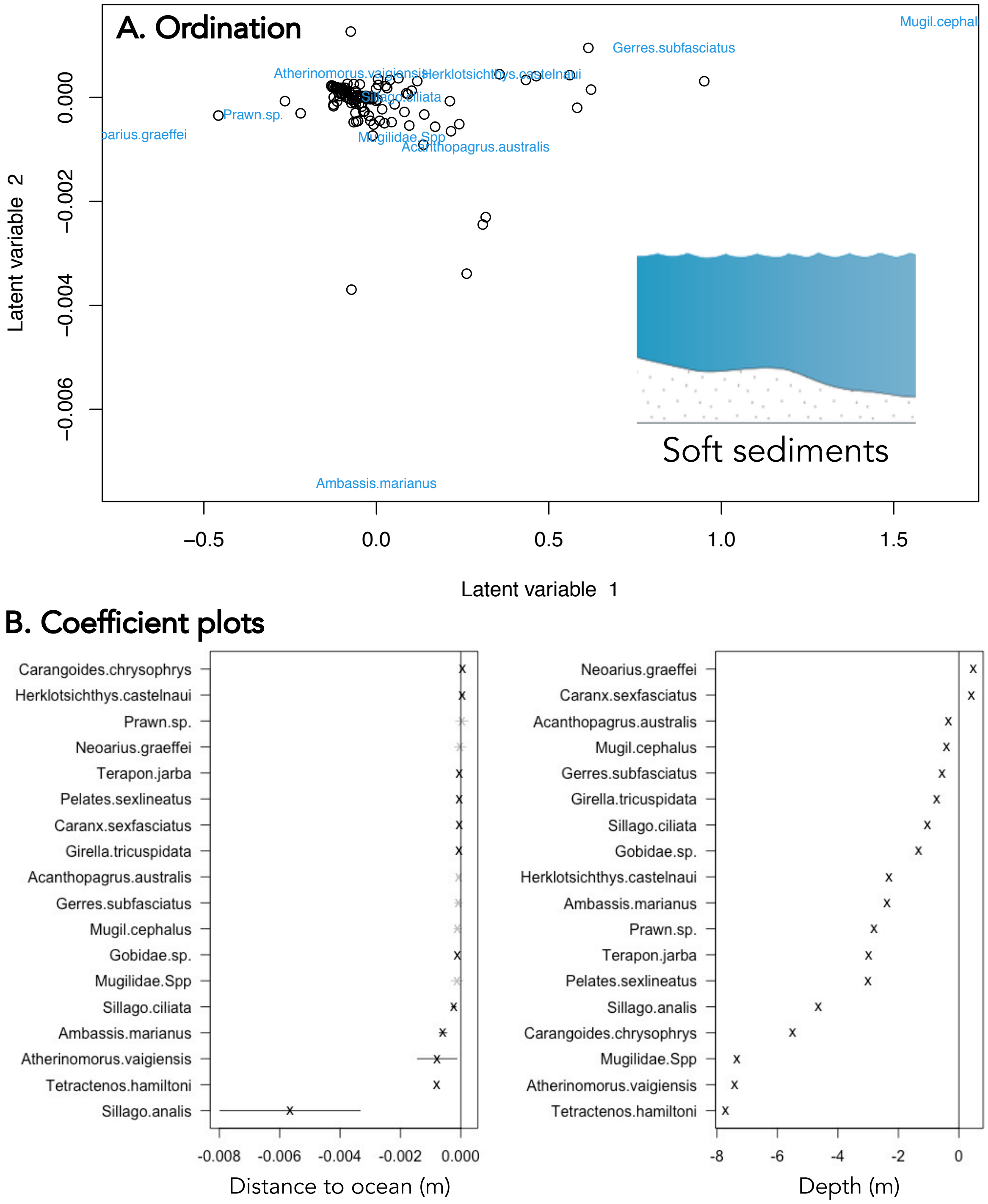
Fish assemblages in mangrove forests were best explained by the proximity of sites to seagrass, the area of seagrass within 500m, and the coverage of algae and mud at the site (Table 3). Silver biddy *Gerres subfasciatus* and estuary perchlet had very similar relationships with these variables from the best fit ManyGLM, but these were fundamentally different to southern herring *Herklotsichtyes castelnaui* and pacific blue eye *Pseudomugil signifier* (Figure 26A). Most species were in greater abundance at mangrove forests that were nearer to, and with a greater extent of seagrass nearby (Figure 26B). Approximately two thirds of species were more abundant at sites with greater mud coverage, but the remaining species were more abundant at sites with lesser mud coverage (Figure 26B). Finally, most species were more abundant at sites with a lower coverage of algae among the mangroves (Figure 26B).

Fish assemblages in salt marshes were best explained by the proximity of sites to intertidal flats and the area of mangroves within 500m of each site (Table 3). Longnose trevally *Carangoides chrysophrys* and southern herring had fundamentally different relationships with variables from the best fit ManyGLM, and remaining indicator species all shared similar relationships (Figure 27A). Approximately 50% of species were in higher abundance at sites with greater extent of mangroves within 500m, and the other half were lower in abundance. Conversely, approximately two thirds of species were more abundant at salt marshes nearer to intertidal flats, with the remaining more abundant at salt marshes more distant from intertidal flats (Figure 27B).

Fish assemblages in seagrass meadows were best explained by the area of seagrass and mangroves within 500 m, and the average coverage of *Zostera* at the site (Table 3). Estuary perchlet and yellowfin bream *Acanthopagrus australis* had fundamentally different relationships with variables from the best fit ManyGLM, and remaining indicator species all shared similar relationships (Figure 28A). Most species were more abundant at seagrass meadows that were smaller and had less mangroves nearby. Approximately 50% of species were more abundant at sites with greater *Zostera* cover, with the remaining more abundant at sites with lower *Zostera* cover (Figure 28B).

Table 3 List of variables included in the best fit ManyGLM for each ecosystem, and their P and X2 values

Ecosystem	**Best fit model variables**			
Soft sediment (Figure 23)	Distance to ocean X^2=58.4, P<0.01	Water depth X^2=52.6, P<0.01		
Log snag (Figure 24)	Distance to ocean X^2=175.33, P<0.01	Distance to salt marsh X^2=86.19, P<0.01	Intertidal area X^2=72.6, P<0.01	
Rocky outcrops (Figure 25)	Distance to ocean X^2=79.1, P<0.01	Distance to mangroves X^2=82.3, P<0.01	Distance to urban X^2=66.5, P=0.03	
Mangroves (Figure 26)	Distance to seagrass X^2=72.93, P<0.01	Seagrass area X^2=72.62, P<0.01	Algae coverage X^2=59.4, P<0.01	Mud coverage X^2=65.25, P=0.01
Salt marsh (Figure 27)	Distance to intertidal flats X^2=50.8, P=0.02	Mangrove area X^2=46.2, P=0.03		
Seagrass (Figure 28)	Seagrass area X^2=52.5, P=0.001	Mangrove area X^2=43.27, P<0.01	*Zostera* coverage X^2=43.61, P=0.03	


A. Ordination

B. Coefficient plots

Figure 23 Generalised linear latent variable model (GLLVM) ordination illustrating sites and the top 10 indicator species for soft sediment sites (A), and GLLVM coefficient plots (B). The ordination plot is calculated using variables from the best-fit ManyGLM, and the nearer two species are in the ordination, the more similar their relationships with the best-fit variables. In the ordination (panel A). X axis values in the coefficient plots are essentially effect sizes, with species positioned in positive values having positive correlations with that variable, and vice versa. Error bars are 95% confidence intervals, and species whose relationship with a variable overlaps with zero (i.e. not significant relationships) are highlighted in grey.

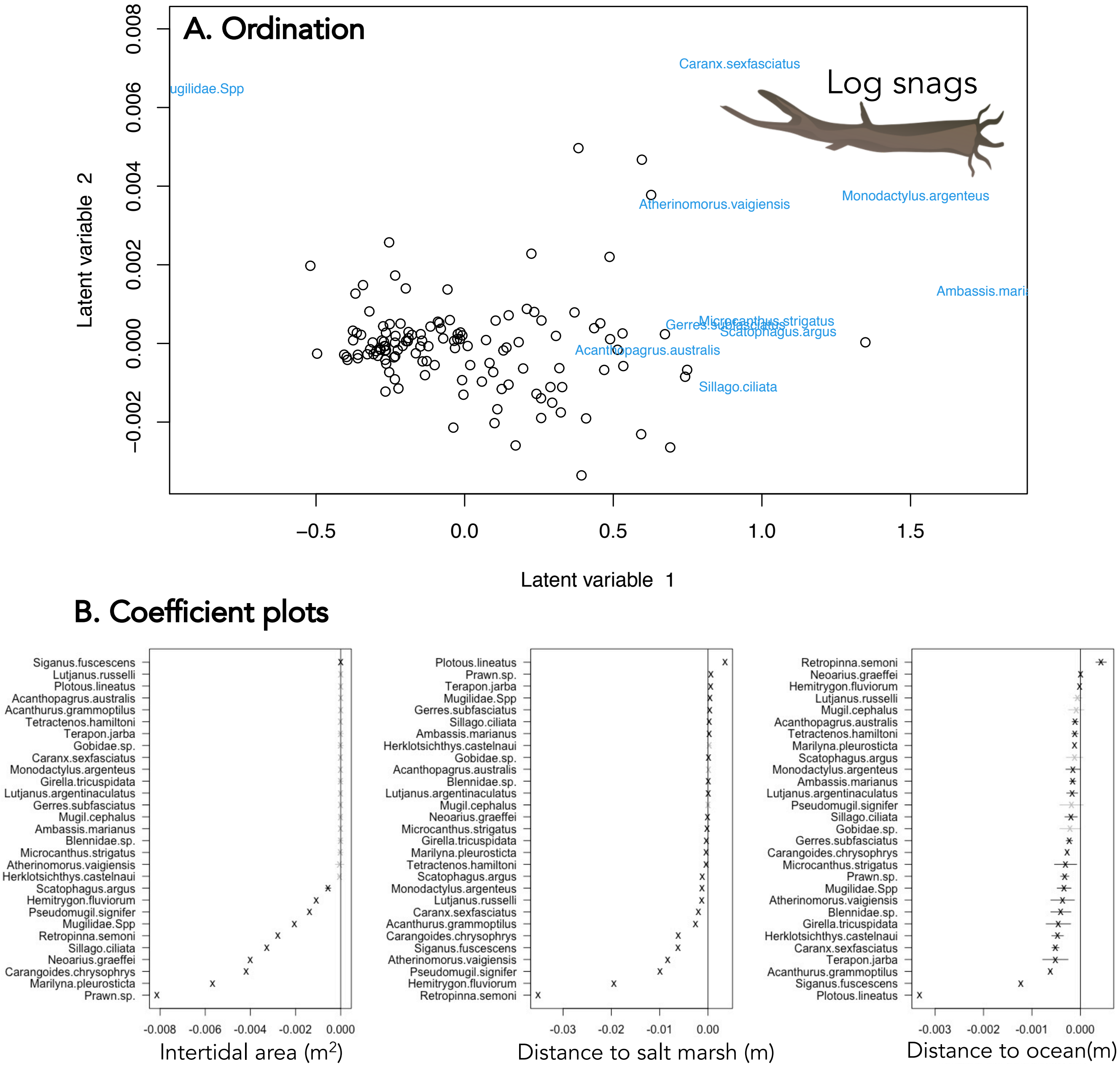


Figure 24 Generalised linear latent variable model (GLLVM) ordination illustrating sites and the top 10 indicator species for log snag sites (A), and GLLVM coefficient plots (B). The ordination plot is calculated using variables from the best-fit ManyGLM, and the nearer two species are in the ordination, the more similar their relationships with the best-fit variables. In the ordination (panel A). X axis values in the coefficient plots are essentially effect sizes, with species positioned in positive values having positive correlations with that variable, and vice versa. Error bars are 95% confidence intervals, and species whose relationship with a variable overlaps with zero (i.e. not significant relationships) are highlighted in grey.

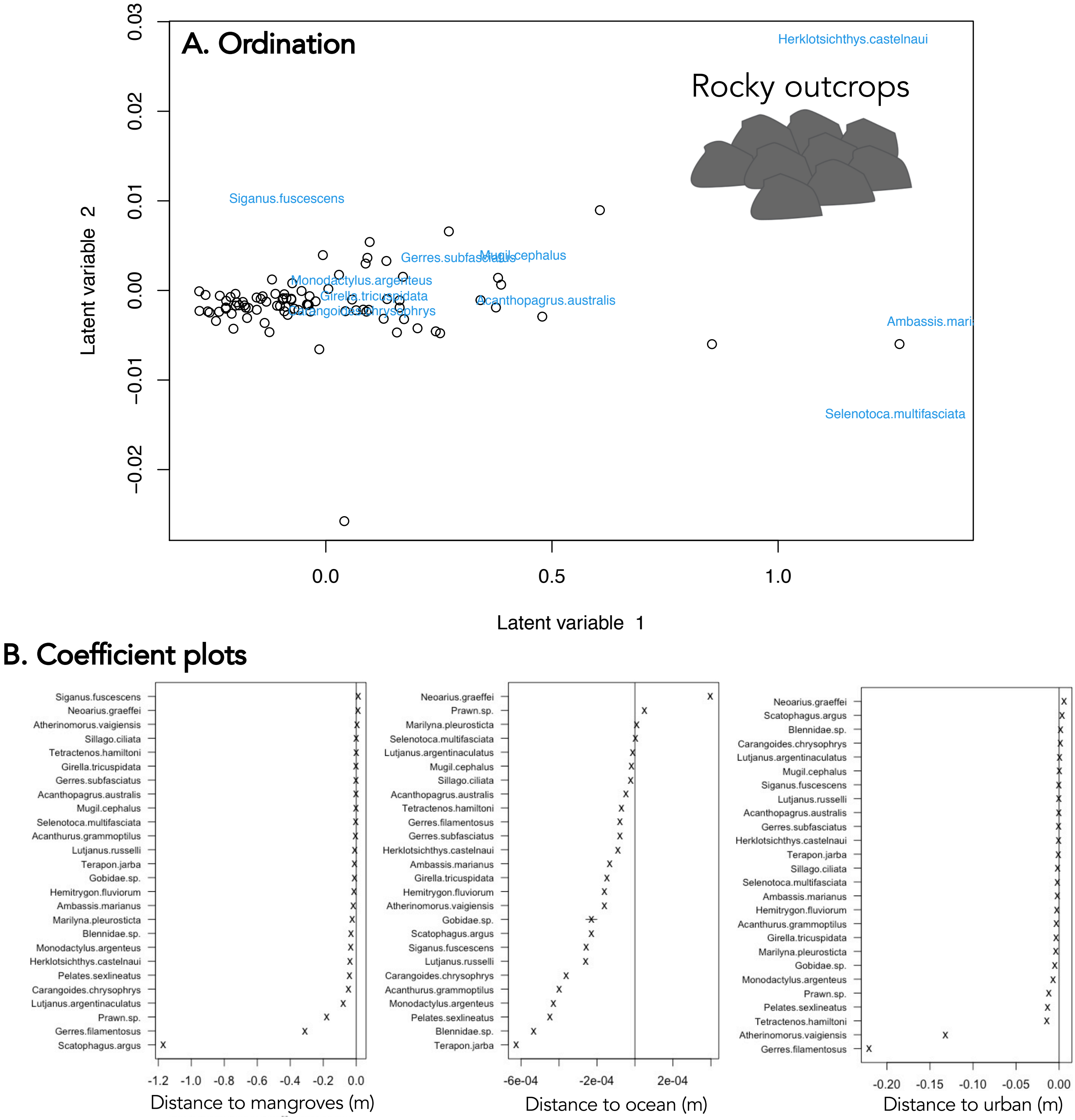


Figure 25 Generalised linear latent variable model (GLLVM) ordination illustrating sites and the top 10 indicator species for rocky outcrop sites (A), and GLLVM coefficient plots (B). The ordination plot is calculated using variables from the best-fit ManyGLM, and the nearer two species are in the ordination, the more similar their relationships with the best-fit variables. In the ordination (panel A). X axis values in the coefficient plots are essentially effect sizes, with species positioned in positive values having positive correlations with that variable, and vice versa. Error bars are 95% confidence intervals, and species whose relationship with a variable overlaps with zero (i.e. not significant relationships) are highlighted in grey.

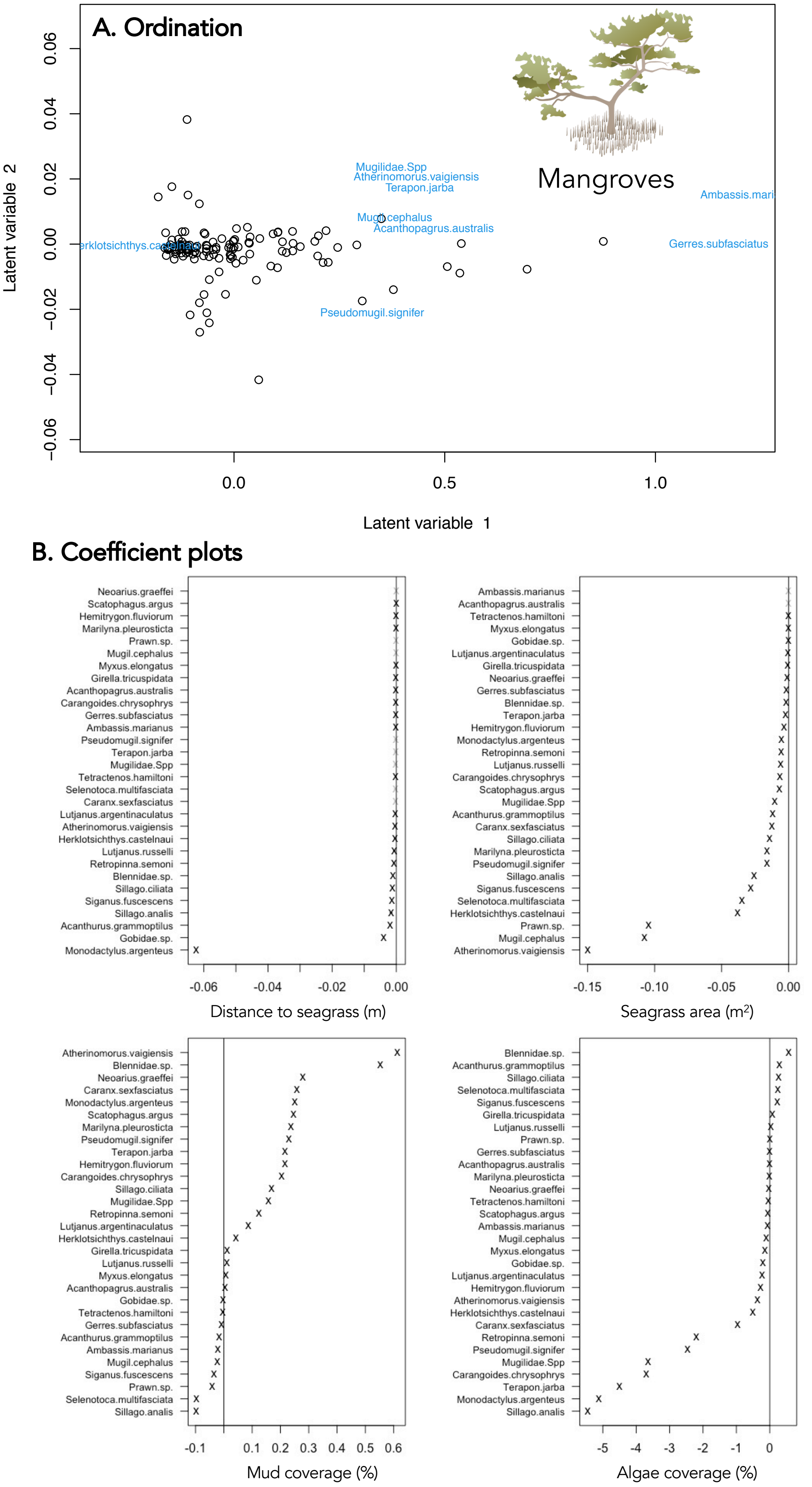


Figure 26 Generalised linear latent variable model (GLLVM) ordination illustrating sites and the top 10 indicator species for mangrove sites (A), and GLLVM coefficient plots (B). The ordination plot is calculated using variables from the best-fit ManyGLM, and the nearer two species are in the ordination, the more similar their relationships with the best-fit variables. In the ordination (panel A). X axis values in the coefficient plots are essentially effect sizes, with species positioned in positive values having positive correlations with that variable, and vice versa. Error bars are 95% confidence intervals, and species whose relationship with a variable overlaps with zero (i.e. not significant relationships) are highlighted in grey.

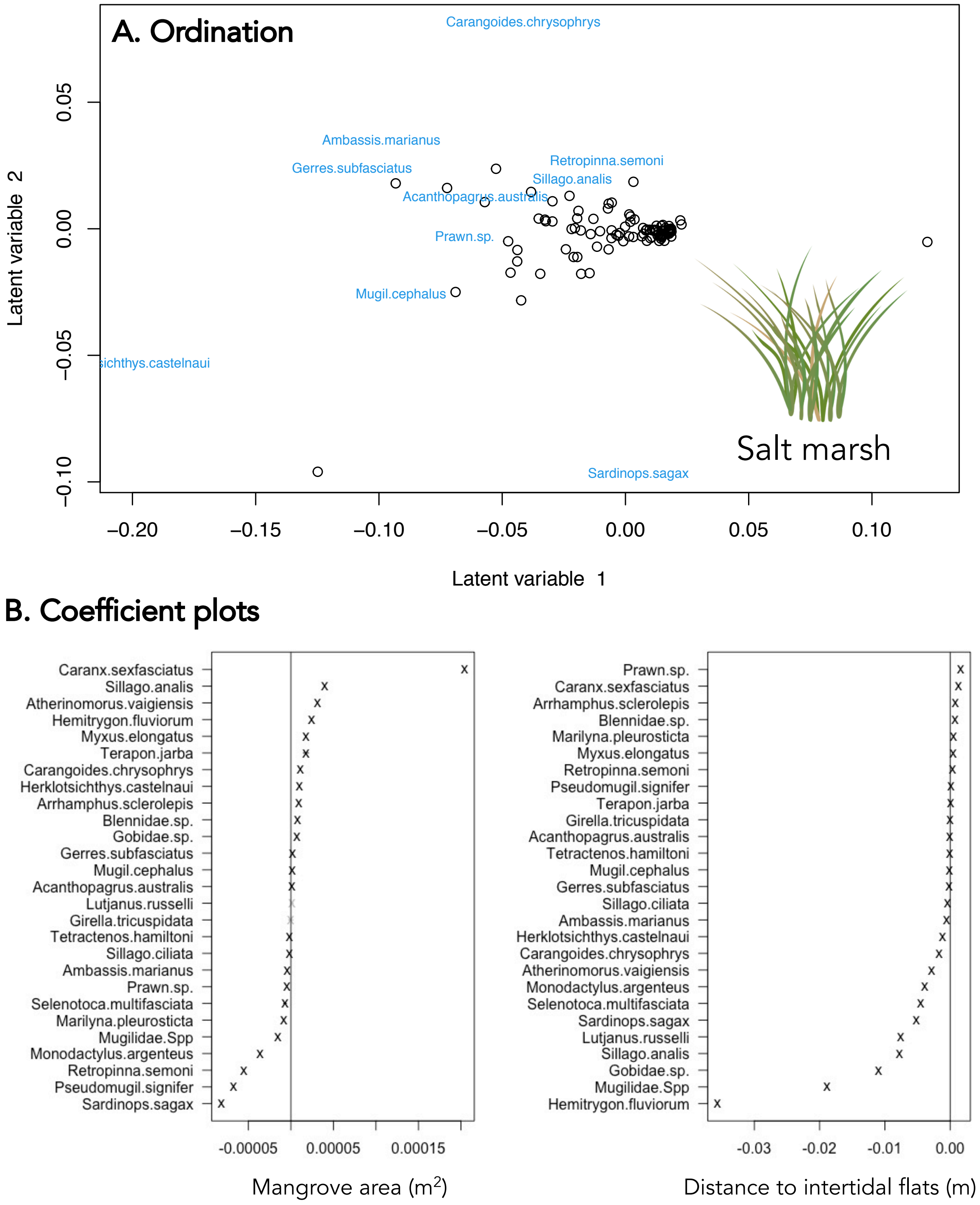


Figure 27 Generalised linear latent variable model (GLLVM) ordination illustrating sites and the top 10 indicator species for salt marsh sites (A), and GLLVM coefficient plots (B). The ordination plot is calculated using variables from the best-fit ManyGLM, and the nearer two species are in the ordination, the more similar their relationships with the best-fit variables. In the ordination (panel A). X axis values in the coefficient plots are essentially effect sizes, with species positioned in positive values having positive correlations with that variable, and vice versa. Error bars are 95% confidence intervals, and species whose relationship with a variable overlaps with zero (i.e. not significant relationships) are highlighted in grey.

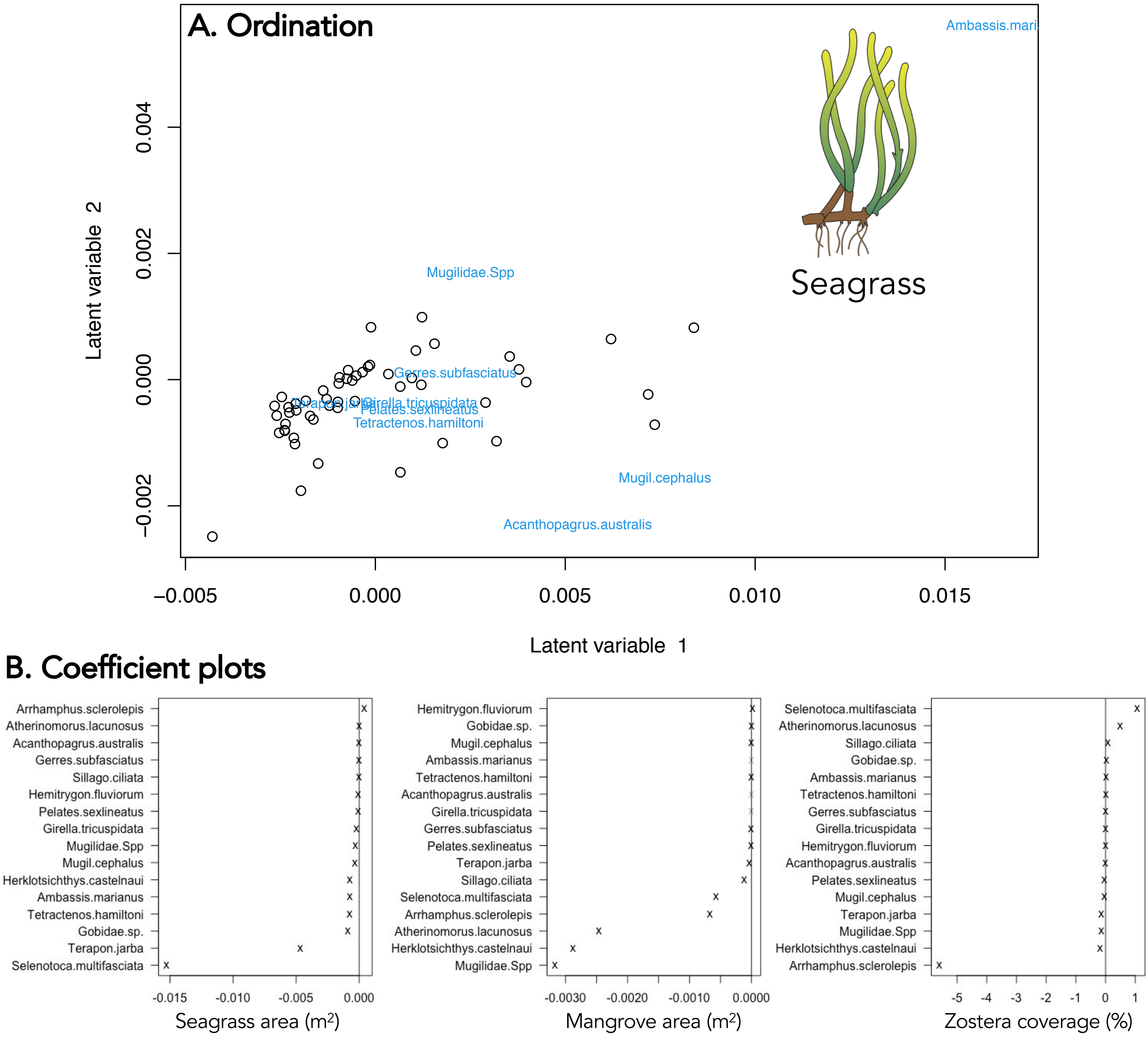


Figure 28 Generalised linear latent variable model (GLLVM) ordination illustrating sites and the top 10 indicator species for seagrass sites (A), and GLLVM coefficient plots (B). The ordination plot is calculated using variables from the best-fit ManyGLM, and the nearer two species are in the ordination, the more similar their relationships with the best-fit variables. In the ordination (panel A). X axis values in the coefficient plots are essentially effect sizes, with species positioned in positive values having positive correlations with that variable, and vice versa. Error bars are 95% confidence intervals, and species whose relationship with a variable overlaps with zero (i.e. not significant relationships) are highlighted in grey.

Conclusions and Recommendations

Coastal ecosystems in estuaries provide a suite of key benefits to people, including the provision of catchable fish, and the support of biodiversity. Thoroughly understanding the environmental variables that most influence the abundance and diversity of fish at individual sites within estuaries is crucial in optimising management that seeks to maximise these benefits. While it is increasingly well understood that both habitat condition and landscape context can work separately to modify the assemblage structure of fish in estuaries, little is known about the relative importance of these two groups of variables, and whether and how they combine to affect fish assemblages.

In 2020, we sought to address this key knowledge gap by surveying fish assemblages at six habitats across the full estuarine stretch of 13 estuaries in southeast Queensland. We identified significant fish diversity in the estuaries of southeast Queensland, and this was relatively evenly spread across habitats and estuaries. The results of spatial analyses in 2020 indicate that the predominant driver of fish assemblages on different habitats in southeast Queensland is the spatial context of sites within the broader estuarine landscape. This encompasses the size and position of both the ecosystem in which sites are placed, and the size and position of nearby alternate habitats across the seascape. These effects outweigh the effects of local habitat condition for all except two habitats, where assemblages at these two habitats were explained by a combination of both seascape context and habitat condition metrics. Therefore, fish assemblages at all ecosystems were either fully, or in some way explained by their position within the broader context of the estuary. These findings suggest that managing the diversity of ecosystems broadly across seascapes is crucial in maximising the abundance and diversity of fish in estuaries. Similarly, maximising the extent of key ecosystems should be a focus when management seeks to increase the abundance and diversity of fish assemblages. Broadly, a focus on habitat condition, as opposed to extent and connectance, may be a less valuable proposition. In this sense, reaching a reasonable level of habitat condition across seascapes, and then seeking to maximise extent is likely to provide the maximum ecological outcomes for fish in estuaries.

Surveys in 2021 will focus on further disentangling the effects of the variables we established here as important for individual habitats. Consequently, we will resurvey all sites surveyed this year, as well as all significant drivers of fish assemblages within each ecosystem. This will enable us to address objective three of the broader project; optimising ecological restoration priorities and plans. Here, we will provide recommendations for how and where different habitats should be restored (i.e. type, size, position and arrangement) to maximise their ecological functioning across the estuaries of southeast Queensland. This will include statistical models and maps of recommended restoration locations for each habitat, and guidelines for the composition, complexity and density of species to be established at restoration sites.

In 2020, we were challenged by the accuracy of existing Queensland Government habitat mapping in the upper reaches of the estuaries we sampled. For example, narrow ‘veneers’ of mangroves that occur along the verges of estuaries are not clearly identified in broader habitat map layers, but are clearly crucial in explaining the patterns we found here. In 2020, we addressed this challenge by using aerial imagery from NearMap (NearMap 2020) to ground truth our distance measures, and to help calculate seagrass extent. While this approach satisfies distance measures in our analyses, more accurate estimates of areal extent are required for future analyses. Consequently, USC would like to take two approaches to improve this crucial consideration in 2021. Firstly, USC will discuss with HLW whether there are better maps available for our study purposes; especially for mangroves, salt marsh and seagrass. Secondly, USC will undertake drone mapping exercises in 2021 at locations where habitat maps are lacking or poorly defined; principally in the upper reaches of our survey extent within each estuary. We look forward to further refining out approach to spatial mapping and predictive models using these maps in 2020.

Surveys in 2021 will cover the same spatial extent and estuaries as those samples in 2020. Surveys will commence in June 2021 (again, the same as for 2020). The next USC annual report will be submitted in December 2021, and will address outcome 2- from objective 3, based in 2020 and 2021 surveys;

- To provide recommendations for how and where different habitats should be restored (i.e. type, size, position and arrangement) to maximise their ecological functioning across the estuaries of southeast Queensland. This will include statistical models and maps of recommended restoration locations for each habitat, and guidelines for the composition, complexity and density of species to be established at restoration sites.

The USC team welcomes the opportunity to further discuss the 2020 results with Healthy Land and Water, and any stakeholders, and will present these results to the EHMP Steering Committee at a date to be confirmed.

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