FINAL REPORT

Life history specific habitat utilisation of tropical fisheries species

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Executive Summary

This project, undertaken by the College of Science and Engineering, James Cook University, aimed to develop a detailed understanding of the sequence of habitats required by inshore Australian fisheries species at different stages of their life-histories. Coastal fisheries species from around Australia were considered, although direct research was conducted only in representative areas of North Queensland between 2013 and 2015. Information from various sources was used, including expert knowledge, literature reviews and direct research (video camera drops, analysis of recreational catch data and satellite imagery). Information was compiled and summarised into an easily understandable form that can be used by different stakeholders, including management, which can use it for example to provide the basis for strategic decisions on the optimal siting of developments or to direct environmental offsets to optimise their benefits to fisheries.

Many tropical fishery species rely on a range of systems (estuaries, tidal wetlands shallow coastal waters) to complete their life cycle. These systems provide important reproduction, feeding, refuge and nursery grounds. Although it is important to determine the value of the different habitats for the different life-stages of each species, this has only been appropriately detailed in very few cases. More often, there is no comprehensive information about the range of habitats occupied throughout ontogeny, or their relative importance. Critically, there is almost no information about the first habitats used by very small juveniles, even though the availability and quality of these habitats has been identified as a critical bottleneck determining nursery ground success. Moreover, a critical aspect of the value of habitats includes the assemblage of interacting habitats, meaning it is important to understand the importance of the connectivities between the different habitats for each species. Although the integrity of these connectivities is crucial for health of fisheries species' populations, our understanding of these connectivities is still largely insufficient.

This project aims to develop detailed models of the life history stage-specific habitat utilisation for key coastal and estuarine fisheries species that can be easily used by different stakeholders (managers, fishers, scientists). These models are presented in the form of matrices that take a fish-centric view and relate fish to their essential habitat mosaic chain (EHMC) in an organised way that facilitates management. In these matrices, we formalise and consolidate information from various sources into an organised fish-habitat understanding. We also present a literature review on the key resources provided by key habitats over life-histories. Finally, we develop specific, achievable measures of fisheries benefits stemming from repair, revitalisation and supplementation work, and provide this information in forms that can inform fisheries habitat management and repair, and value-add to habitat mapping.

Our methodological approaches consisted on firstly establishing a conceptualisation of habitats from the point of view of fish utilisation, which was then used to develop a framework that links fish to their habitats while taking into account their life-history requirements. Several sources of information were used to construct these matrices. Firstly, the literature was reviewed to determine "what is a habitat" in the context of fish life-history utilisation, so that that information could be used to develop a way of conceptualising habitats relevant to management needs. Then, information on habitat use by the different life-stages of fisheries species was obtained through searching the

published literature and the Fishbase database (Froese and Pauly 2016), and through consultation with key experts (recreational and commercial fishers, expert anglers, fisheries officers and scientists). Direct research was also conducted in representative areas of North Queensland (Hinchinbrook Channel) to identify habitat relationships of life-history stages not targeted by fishers (particularly small juveniles). This included underwater video camera drops to provide information on the distribution of sub-tidal habitats in the studied areas, and on the fish species and life-stages that use these habitats. Furthermore, this project developed a new approach of 'Habitat Identification by Catch and Satellite Data' (*Habitat IDxCSD*), using the Hinchinbrook region as a case study. The approach uses open-access satellite data, cross referenced with a large-scale public data set in a desktop analysis.

Based on the information obtained by the different methods, **fish-habitat matrices** that bring together and detail current fish-habitat understanding were constructed for a range of fishery species. These matrices are the key output of the project. They cross-correlate habitat utilisation and life-history phase, and represent a simple and effective means of **communicating** the information to end users. This information can be used as a basis to make strategic decisions on management actions such as determining the optimal siting of developments to minimise impacts on fisheries or directing offsets to the repair/revitalisation of degraded habitats to optimise their benefits to fisheries. This work also provides the information needed to populate coastal habitat maps and classification schemes that will be key contributors facilitating optimised management outcomes. In particular, they will be useful to facilitate the development of specific metrics allowing the quantification of the fisheries benefits stemming from habitat repair.

Thus, potential impacts of this research include improved management practices, reduced risk to resources and the ability to target habitat repair actions appropriately, thereby enhancing resource sustainability. Since this work will enable the relative values of fisheries habitats to be assessed, it will help ensure decision makers clearly understand the services provided by different habitats, how best to minimise impacts and the best ways to develop realistic offsets. Therefore, the understanding gained in this project benefits commercial, recreational and indigenous fishers as well as Australian seafood consumers, by providing managers the information needed to make strategic decisions that rely on understanding the relative values of different habitats to coastal and estuarine fisheries species.

It is however important to note that the matrices developed are only examples specific to north-east Queensland coastal and estuarine waters. The complex and location specific nature of fish-habitat relationships, and the substantial body of information needed as input into the Fish-Habitat Matrices mean that additional work is needed to operationalise the approach for other areas. Future development will require 3 steps: (i) developing a standard approach for capturing, assessing and integrating diverse sources of information for incorporation into the Fish-Habitat Matrices; (ii) working with multiple end-users to test, check, evaluate and update the methodology; and (iii) developing substantive studies to prioritise information needs and conduct the multidimensional studies need to populate the Fish-Habitat Matrices.

Keywords

Australia, Coastal fisheries, Fish, Fisheries management, Habitat management

1. Introduction

1.1 Habitats for Fisheries Species

Coastal ecosystems such as estuaries, tidal wetlands and shallow coastal waters are often highly productive and provide important crucial feeding (e.g. Begg & Hopper 1997), spawning (e.g. Gray & Miskiewicz 2000), and nursery grounds (e.g. Beck et al. 2001, Sheaves et al. 2015) to many fisheries species. However, despite the fact that coastal ecosystems are among the most valuable of earth's ecosystems (Costanza et al. 1997), they are under increasing threat from coastal development (Elliott & Whitfield 2011, Waycott et al. 2009, Bassett et al. 2013). Fisheries are among the most important contributors to the value of coastal habitats (Costanza et al. 1997). The health and resilience of fisheries depend on species being able to access specific resources at particular life-history stages (Levin & Stunz 2005). For most species this requires the use of a series of different habitats or seascape units during the different stages of their life cycle (Nagelkerken et al. 2015). While some life stages may occupy discrete habitats that provide all the resources needed (Tupper 2007), most move across the seascape, linking separate, and often distant, habitats (Sheaves & Molony 2000, Krumme 2009, Davis et al. 2014). Therefore, while management based on static spatial units may be effective in sustaining some species or life stages if all resources required are contained within the protected unit, it will be ineffective if required habitats transcend this managed unit (Sheaves 2009, Edwards et al. 2010). This illustrates the need for a detailed understanding of life-history specific fish-habitat relationships, for an effective management of fisheries resources. This detailed understanding is however lacking for many, if not most, coastal fisheries species (Levin & Stunz 2005, Sheaves et al. 2006), preventing not only the effective management of critical fisheries resources but also hampering the ability to direct development to enhance, rather than degrade fisheries values (Beck et al. 2001). For example, incomplete understanding often results in the closure of large areas of productive fisheries in the hope of protecting an inadequately resolved habitat resource, such as a breeding or nursery area.

Many management and offsets actions are presently unsatisfactory to all users because they are based on incomplete understanding of fish-habitat relationships. This means that the broad-brush management actions that are generally implemented, often lead to poorly targeted offsets that rarely produce tangible gains in ecosystem health or biodiversity, frustrating fishers, environmentalists, developers and governments alike (Sheaves et al. 2014). Not only can carefully designed developments provide new areas of critical habitat to replace habitats damaged in the past, but the opportunity exists for directing mandatory offsets from new coastal developments towards beneficial fisheries outcomes. This has the potential to provide the basis for greatly improved management of coastal fisheries habitats and to help direct effective offset strategies, assist in the design of fisher-friendly infrastructure, and allowing the development of metrics appropriate for the definitive measurement of specific fisheries outcomes from particular offset actions. Consequently, improved understanding of stage-specific habitat requirements of fisheries species is central to both the long-term health of fish stocks and fisheries productivity, and the effective management of coastal development to enhance fisheries values.

1.2 Habitat Classification

The first step in understanding fish habitat use is to develop a suitable habitat classification system to characterise and map the marine environment. While coastal species and ecosystems are studied at a range of spatial and temporal scales, management actions generally focus on discrete and static spatial units that can be most easily defined and mapped, from broad bioregions (e.g. Fernandes et al. 2005) or whole estuaries (e.g. Vasconcelos et al. 2011), to individual systems or habitat units such as mangrove forests, seagrass beds, or reefs (Barbier et al. 2011, Vasconcelos et al. 2014). A number of habitat classification schemes have been developed and generally aim to provide the spatial understanding of marine resources needed for a basis for management and conservation planning and action (Mumby & Harborne 1999, Madden & Grossman 2004, Ball et al. 2006). Although classification schemes vary depending on the specific purpose of the classification (Ball et al. 2006), they are generally organised into a hierarchy of nested elements, with higher levels typically defined at coarser spatial scales (e.g. Madden & Grossman 2004) and predominantly based on geophysical attributes, while biological attributes are often, but not always (e.g. Roff & Taylor 2000), included at lower levels. Most of these schemes culminate with an identified community associated with the lowest level of the hierarchy. These are often termed biotopes, comprised of the habitat plus its associated species assemblage (Costello 2009). This approach, of a hierarchy of structural elements with a community nested at the bottom, is well suited for providing spatial maps of habitat types defined by their dominant biotic assemblages (Diaz et al. 2004, Ball et al. 2006), as a basis for spatial prioritisation (Malcolm et al. 2012), developing surrogates for marine biodiversity (NRSMPA 2000, Costello 2009), and identifying indicator species that can stand as sentinels for habitat quality (Zacharias & Roff 2001). However, by themselves these classification systems usually fail to provide the information necessary for specific fisheries management applications because they focus on managing units of habitat rather than taking a fish-centric view that considers the mosaic of habitats a fish requires for various reasons during its life cycle (St Mary et al. 2000, Moura et al. 2011) and the connections among the components of the habitat mosaic (Nagelkerken et al. 2015).

1.3 How to manage based on habitats

Despite the advances made possible by the detailed and consistent definition of habitats and their associated assemblages, habitat classification only provides a focus for management as long as the community in that habitat, at some point in time, is the target of management. However, this view of a static, idealised community doesn't account for the complex ways that marine animals use their habitats (Sheaves 2009, Nagelkerken et al. 2015). Open life-histories (Caley et al. 1996) and high mobility of many species (Apostolaki et al. 2002) mean that effective management of a species (and by logical implication communities) requires focus on its essential habitat niche, the mosaic of habitats needed by the organism including the connections between those habitats (Weinstein & Litvin 2016). This will often be the case whether the goal is the protection of fisheries assets, the conservation of species, assemblages or processes, or the restoration of ecosystem function. Including complexity also requires accounting for multiple temporal contexts, because organisms use habitat mosaics in different ways relative to different contextual and temporal scales (e.g. daily patterns of use versus life-history utilisation).

Structuring management around protecting habitats can provide a coherent basis for managing fisheries (Rosenberg et al. 2000) and has the added advantage of holistically protecting many other natural resources and the processes associated with the habitat (Gell & Roberts 2003). However, for the concept of 'habitat' to be an optimally useful management target it needs to encompasses all the units that an organism requires to complete the particular function of interest (e.g. nursery occupation) or that it uses over its whole life history (Levin & Stunz 2005). Without that holistic delineation of the essential habitat for a species or function, management is likely to be misdirected. For example, Morris and Ball (2006) produced fisheries habitat suitability models for Port Phillip Bay, Victoria, Australia, based on commercial CPUE of important fisheries species. While this approach produced a useful bay-wide map of the habitats most valuable to the extractive phase of the fishery, it seems unlikely to provide an effective basis for managing the fishery because the approach didn't identify key habitats required by non-exploited components of the target species. Both juvenile whiting *Sillaginodes punctata* (Hyndes et al. 1996) and pink snapper *Pagrus auratus* (Hartill et al. 2004), key species in the Port Phillip Bay study, occupy different nursery habitats to those used by the bulk of their adult fished populations. Consequently, the approach of Morris and Ball (2006) would be unlikely to provide the scale of spatial information necessary for effective whole-of-stock management, particularly because the survival of early life-history stages on population growth rate can be orders of magnitude greater than the survival of later stages (Levin & Stunz 2005). Moreover, without a level of definition that explicitly includes all the habitats needed to support a species or a life-history function, the essential habitat required by the species will be incompletely resolved. This is likely to give the false impression that the management action is appropriate to afford protection to a species, when in fact the habitats that are critical to the species' survival have not been identified (Thrush et al. 2002). Rather, a spatially explicit assessment of habitat utilisation for all life-history stages is required to allow the identification of habitat value relevant to the intended management goals (Jacobson & Hunter 1993, Pinho et al. 2014). Consequently, for habitat characterisation to be effectively incorporated into management it is vital to develop frameworks that link habitat conceptualisations to key characteristics of the target organisms and the dynamic way they use their environment. This means identifying the mosaic of habitats, and the links between them, that are necessary for the organism to carry out the function that is the focus of management, i.e. the *Essential Habitat Mosaic Chain* (EHMC) associated with the function (Fig. 1).

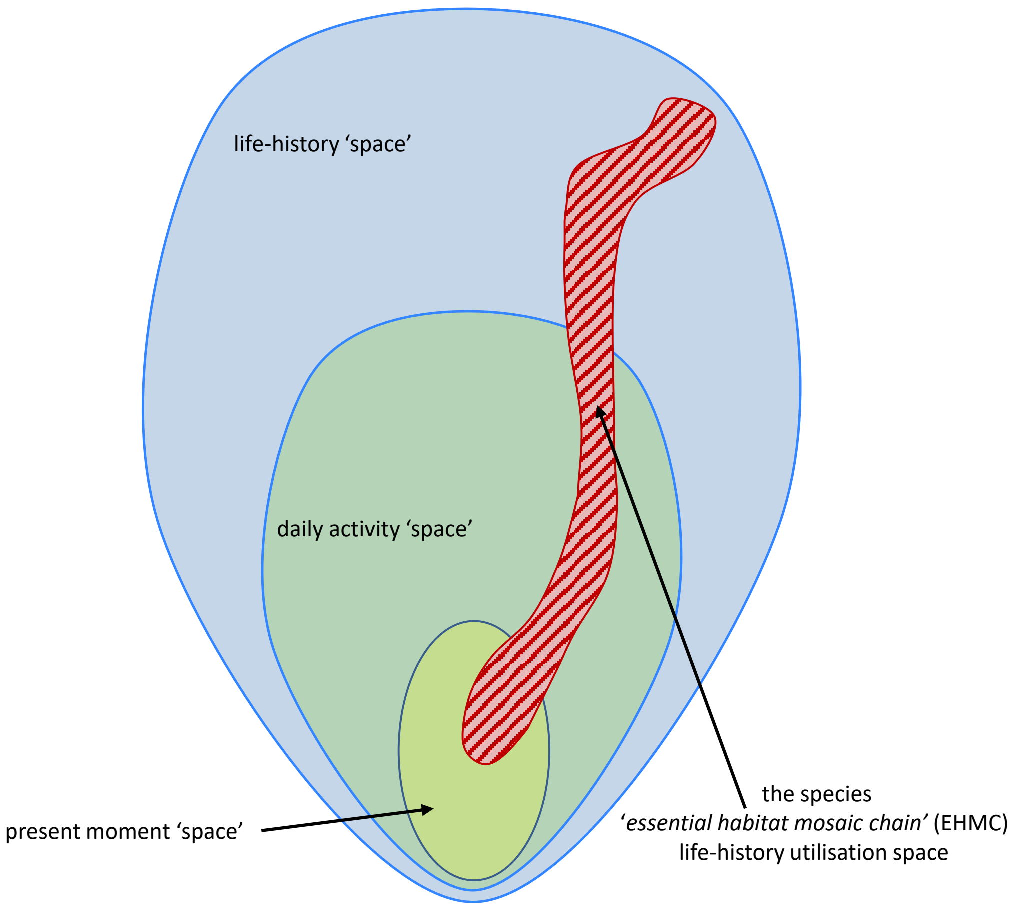

Figure 1. Conceptualisation of a species "essential habitat mosaic chain" (EHMC) life-history utilisation space. A species' position is conceptualised as three nested regions of time-space. A species occupies a particular part of all possible 'present moment' spaces at any particular time. During daily activities (feeding, resting, etc.) it utilises particular parts of all possible 'daily activity' spaces. Throughout its life-history, it utilises particular components of all life-history spaces. Together, these 'spaces' comprise the species' EHMC, with it using particular, definable, habitat components at each stage of its life-cycle to carry out its full suite of life functions.

This project **aims** to develop an understanding of the life-history habitat needs of Australian coastal and estuarine fisheries species to provide the basis for strategic decisions on the optimal siting of developments, directing the development of coastal infrastructure, directing environmental offsets to optimise their benefits to fisheries, and providing the information needed to populate coastal habitat maps that will also be key contributors facilitating these outcomes. We develop a simple approach, based on key coastal and estuarine fisheries species, which takes a fish-centric view and relates fish to their EHMCs in an organised way that facilitates management. Firstly, we establish fish-habitat relationships based on a combination of literature review, direct research and expert interviews, then we establish a conceptualisation of habitats from the point of view of fish utilisation, develop a framework suitable for linking fish to their habitats that accounts for the reality of their life-history requirements. Finally, we investigate some ways in which the framework could be used based on example tropical fisheries species.

2. Objectives

This project focuses on developing a robust understanding of the sequence of habitats required by key inshore Australian fishery species at different life-history stages. The **aim** is to develop a typological understanding based on published and unpublished information and on targeted research in representative areas, with information from the representative areas used to develop a robust knowledge-base of life-history habitat use and key connectivities that is sensitive to changes across the different regions. The specific **objectives** are to:

1. develop detailed models of the life history stage-specific habitat utilisation of key coastal and estuarine fisheries species at the most detailed mensurative level possible;
2. formalise and consolidate fisher knowledge on fish-habitat relationships into an organised fish-habitat understanding;
3. develop estimates of the relative contributions of different juvenile habitats to adult populations, and estimates of the relative value per unit area of alternative stages-specific habitats to fisheries stocks;
4. quantify the key resources provided by critical habitats over life histories
5. develop specific, achievable measures of fisheries benefits stemming from repair, revitalisation and supplementation work; and
6. provide information from points 1-5 in forms that can inform fisheries habitat management and repair, and value-add to habitat mapping.

3. Methods

3.1. Objective 1 - Develop detailed models of the life history stage-specific habitat utilisation of key coastal and estuarine fisheries species

In this part of the project, we produced a broad assessment of coastal fish habitat relationships, unprecedented in both breadth of habitats surveyed and depth of detail. Focused on the fish habitat protection area of the Hinchinbrook region, cutting edge underwater video sampling methods were combined with new statistical techniques to provide the latest 'best practice' model of fisheries habitat. Three years of sampling has uncovered life-cycle specific habitat utilisation patterns for many fisheries species, new and important habitat types, and intricate links between habitats in support of fisheries.

Details of this part of the study can be found in Appendix 2.

3.2. Objective 2 - Formalise and consolidate fisher knowledge on fish-habitat relationships into an organised fish-habitat understanding

In this part of the project, we developed and evaluated a new approach of Habitat Identification by Catch and Satellite Data (*Habitat IDxCSD*) to identify key fish-habitat relationships, using the Hinchinbrook area as a case study. This method involves using Google Earth satellite imagery to identify habitats at the scale of fish occurrence reports in a large, archived data set. In this case, the fish occurrence data takes the form of angler tagging catch-and-release data, but the method could equally be applied to data collected by governments, fishing organisations, or in citizen science projects. This provides two robust data sets that can be aligned and analysed at a management-relevant scale. The three main objectives of this study were 1) to develop and test the approach '*Habitat IDxCSD*'; 2) use the *Habitat IDxCSD* to identify important fish habitats in the Hinchinbrook Channel for key fish species, and 3) use targeted surveys of expert anglers to cross-validate outputs from the *Habitat IDxCSD* methodology.

Details on this part of the study can be found in Appendix 3.

3.3. Objective 3 - Develop estimates of the relative contributions of different juvenile habitats to adult populations, and estimates of the relative value per unit area of alternative stages-specific habitats to fisheries stocks

This part of the study was based on underwater video sampling techniques, as in Section 3.1. The new sampling methodology was developed, that can be used in a range of habitat types and that therefore has the advantage of producing results that are comparable between habitats. We combine the use of this sampling technique with new statistical tools to produce a new 'best practice assessment' of the fisheries value of coastal habitats.

Details on this part of the study can be found in Appendix 2.

3.4. Objective 4 - Key resources provided by critical habitats over life histories

Stable isotope analysis is a useful tool to determine the key resources provided by the different habitats over life histories, and it has been used in several studies around Australia. The diversity of habitats and habitat mosaics along the Australian coast, coupled with the high diversity of fishery species and their life-histories, makes it unrealistic to empirically study the resources for the different life-history stages of all species within the time-frame of the present project. Therefore, we conducted a literature review on the current knowledge on the key resources provided by critical habitats to coastal fishery species around Australia, which can be found in Appendix 4. There, we focus on the key habitat units that are widely studied and generally considered in management: mangroves, saltmarshes, seagrass beds and coral and rocky reefs (Beck et al. 2001).

3.5. Objective 5 - Develop specific, achievable measures of fisheries benefits stemming from repair, revitalisation and supplementation work

Healthy coastal wetlands and estuaries and the habitats that comprise them play vital roles in supporting coastal food webs and fisheries production, acting as critical feeding, nursery and reproductive areas for many important species. However, Queensland's coastal wetlands are severely degraded due to impacts of a diversity of anthropogenic stressors. As a consequence, their function has been compromised by substantial losses of some of the most productive of aquatic habitats. Careful management and repair and revitalisation actions are therefore urgently needed. These actions need to be prioritised and their success evaluated. In this part of the study, we investigate how the value of northern Australia's coastal wetlands and estuaries can be measured in robust, valid and meaningful ways. Consequently, we identify the pre-requisites for the development of achievable measures of fisheries benefits of habitat repair and revitalisation actions. In doing this, we (a) examined the need for measures of the values of coastal wetlands and estuaries and what form appropriate estimates should take, (b) assessed appropriate methods for collecting necessary data and the extent of data currently available, and (c) determined the additional studies needed to convert the available data into useable measures of fisheries benefits.

See Appendix 5 for details on this part of the study.

3.6. Objective 6 - Provide information from points 1-5 in forms that can inform fisheries habitat management and repair, and value-add to habitat mapping

The information obtained by the different approaches used in this study (Appendices 2-5) was complemented with published information, fisheries documentation (see below) and information in FishBase (Froese and Pauly 2016) on habitat use to first develop an operational conceptualisation of fish habitats (Section 3.6.1) and then to construct **fish-habitat matrices** (Section 3.6.2) for the different fishery species. These matrices cross-correlate habitat utilisation and life-history phase for key fishery species and represent a simple means of **communicating** the information to end users.

3.6.1. Conceptualising fish habitats

The first step in this part of the study was to establish an organised understanding of what a habitat is from a fish's perspective. This utilised information from an extensive review of the published literature combined with information from interviews with expert anglers (see Appendix Table A3-1 for questions and compiled responses). In answering the question "**What is a habitat**?" in the context of fish life-history utilisation, it was critical to recognise both the dynamic nature of habitat utilisation, with the different habitats used for different purposes, and the scaling of habitat use, including the mosaic of habitats used throughout the different species life-histories. Figure 2 conceptualises four levels of 'habitat' relevant to fishery species: *process zone, macro-habitat, meso-habitat and micro-habitat*. This hierarchical scheme is not the only way that 'habitats' can be conceptualised, but it is one that seems to work well for many applications and provides a simple way to construct habitat descriptions that are relevant to fisheries species/habitat relationships. This classification system was developed to be consistent with the habitat attribution and typology currently under development in the *Estuarine and Marine Classification Project* being the Queensland Wetlands Program (QWP) in collaboration with Department of Agriculture, Fisheries and Forestry (DAFF), Department of

Science, Information Technology, Innovation and the Arts (DSITIA), Department of National Parks, Recreation, Sport and Racing (NPRSR), Gladstone Ports Corporation (GPC) and the Department of Environment and Heritage Protection (EHP), and supported by James Cook, Griffith and Queensland Universities, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the Great Barrier Reef Marine Park Authority (GBRMPA). This proposed hierarchical system is aimed at providing a framework and principles to enable a consistent regional ecosystem-style mapping for estuarine and marine environments, allowing the development of systematic tools for a planning and management (e.g. to support decisions on offsets, zoning, development assessment, etc.).

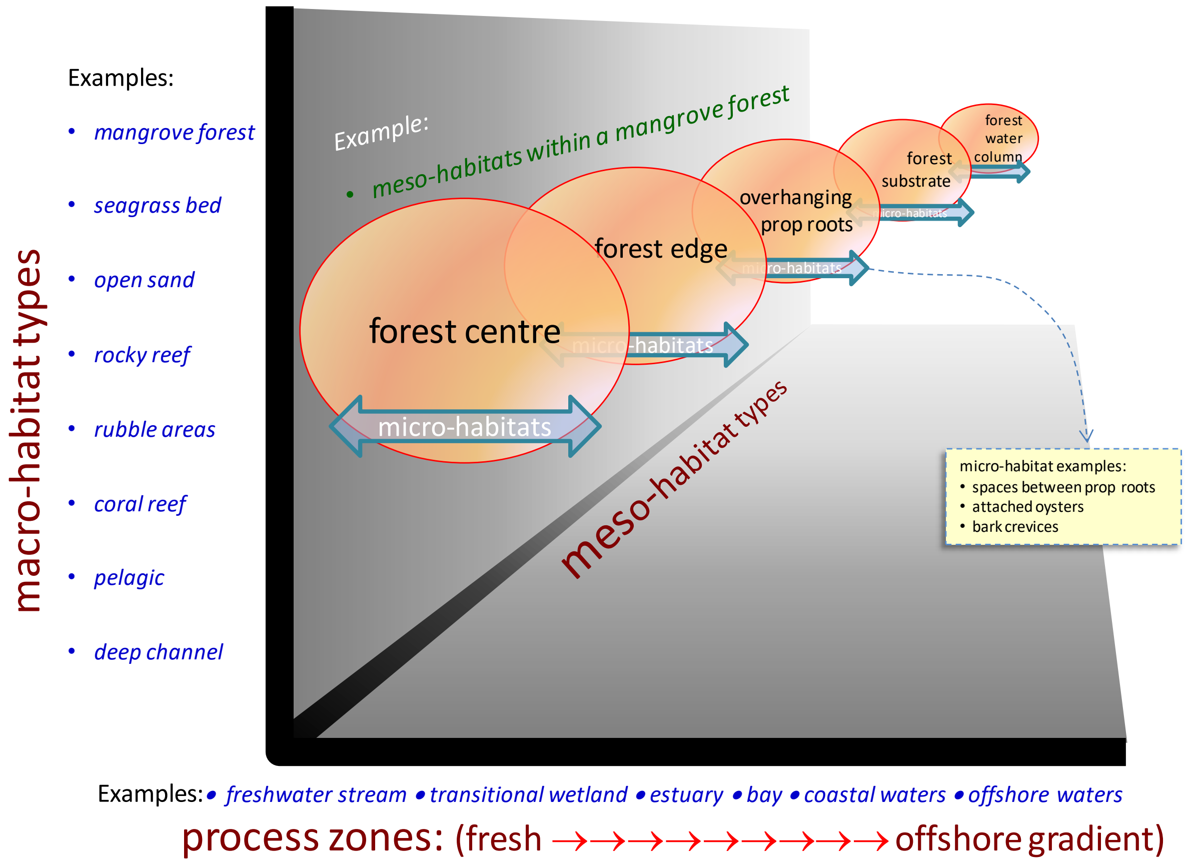

Figure 2. Conceptualisation of the four 'habitat' axes relevant to coastal fisheries species.

A nested habitat hierarchy. Figure 2 conceptualises a nested hierarchy of four habitat utilisation axes relevant to fisheries species and the way they use the environment. Although not the only way that 'habitats' can be conceptualised, this provides a simple conceptual framework for developing simple tools for the identification of essential habitat mosaic chains (EHMCs). A fish's EHMC comprises the ensemble of these nested habitat components it utilises in carrying out all its life-supporting activities. The EHMC for a species therefore represents the particular subset of all possible regions of space it occupies across time scales from birth through its whole life-history (Fig. 1).

The four habitat axes:

Process zones:

A fish's whole life-history occurs within one or more process zones. Process zones comprise a gradient of overlapping environments from freshwater to offshore that aligns conceptually with a gradient of terrestrial to offshore influences. Process zones follow the Thorp et al. (2006) concept of 'functional process zones' that represent areas where local hydrogeomorphic and physiochemical conditions provide particular sets of physical conditions and resources that determine distinctive ecosystem structure and function. Fish species tend to be found within one *process zone* during particular parts of their life-cycles or move into *process zones* for particular purposes such as feeding or spawning. For our example of Australian coastal fisheries species, 15 process zones were identified, from upland freshwater streams to the open ocean.

Relevance: Conceptualising and understanding resource utilisation at the level of process zones is important to management because process zones define the areas species utilise for particular life-history functions (e.g. nursery grounds). However, by themselves process zones will rarely provide a suitable basis for management decisions because they are so large in scale that they provide little specific information on the resources that are used by fisheries species. Also, they generally occur at scales greater than the human activity that is to be managed (e.g. the construction of a retaining wall) (Levings 1981). In other cases, process zones are unsuitable for management because, as well as aggregating many resource patches that are relevant to management objectives, each process zone includes many lower level 'habitats' not important to the targets of management. Consequently, management at the process zone scale can result in decisions that unnecessarily disadvantage particular stakeholders, as for example in the case of the controversy about the fisheries benefits of GBR zoning (e.g. Fletcher et al. 2014, Emslie et al. 2015). Moreover, information aggregated at the process-zone scale will usually provide little specific detail on the resources used by fisheries species. However, a detailed understanding of the roles of process zones can have a substantial impact on management thinking. For instance, realisation of the importance to diadromous species of connectivity across estuary-fresh transitional zones (Davis et al. 2014) has led to the understanding of the importance of protecting these areas even though they are only used transiently (Levin and Stunz 2005).

Macro-habitats:

Nested within process zones are macro-habitats (Fig. 2); large homogeneous units of the seascape characterised by particular biological (e.g. mangrove forests, seagrass beds, coral reefs) or hydro-geomorphological (e.g. open sandy or rubble areas, rocky reefs, sub-tidal channel, pelagic waters) attributes that are identifiable at scales of tens to hundreds of metres. Some macro-habitats occur in a number of process zones but others are unique to a single zone.

Relevance: Macro-habitats relate to the 'daily activity space' (Fig. 1), with an individual utilising one or a number of macro-habitats in conducting its everyday activities (feeding, seeking refuge, etc.). Consequently, macro-habitats are the level at which a species is likely to be mapped into a habitat classification scheme. Their easy identification and the ability to determine species utilisation makes *macro-habitats* important targets for management. *Macro-habitats* can also be directly linked to utilisation by fishery species for particular purposes via a range of field sampling approaches (e.g. netting and video studies). However, as with process zones, macro-habitats alone do not provide optimal units for management. Focussing only on macro-habitats would mean that in many cases management would extend inefficiently to macro-habitats in process zones where action was irrelevant to the reason for management, for instance because the macro-habitat was only utilised in one process zone (Fig. 3). In contrast, macro-habitats embedded within particular process zones (i.e. a combination of the first two axes of Fig. 2) provide a conceptualisations of habitat that allows much more precise focussing of management than afforded by either process zones or macro-habitats alone. For instance, combining process zone and macro-habitat understanding would allow identification of the value of rubble areas in the lower parts of estuaries as early nursery habitats for a number of species of snappers (Lutjanidae) such as the mangrove jack *Lutjanus argentimaculatus* (Fig. 4). However, without further development the process zone × macro-habitat combination falls short of the ideal focus for management because what is really required is identification of the full suite of process zone × macro-habitat combinations that comprise the EHMC relevant to a specific management objective.

Meso-habitats:

Meso-habitats are a subdivision of *macro-habitats* into their functional component parts. Although meso-habitats are nested within macro-habitats they can be categorised in a number of ways depending on the purpose of the conceptualisation. For instance, a mangrove forest could be decomposed into subdivisions based on its horizontal spatial arrangement (e.g. landward forest edge, forest centre, seaward forest edge, etc.) (Fig. 2) or into vertical categories (e.g. substrate, roots, trunks, leaves, etc.). These divisions overlap so the conceptualisations are not entirely independent of each other. Allowing different meso-habitat conceptualisations for different purposes is a pragmatic construct aimed at overcoming the problem of trying to partition macro-habitat space in a strict framework when there is really no simple, consistent way to impose a logical hierarchy. Without this flexibility, categorisation at this, and lower levels, would be unworkable, with any one schema unable to fit different purpose-specific needs.

Relevance: Meso-scale habitats are the parts of the environment where a fish is located at a particular point in time, i.e. the *present moment space* (Fig. 1). They play an important part in the way fisheries species utilise macro-habitats so are important to science. The small, local scale of meso-habitats means they will be unsuitable targets for many management actions. For instance, even if one component of a seagrass bed is identified as having particularly high value (e.g. Smith et al. 2011), it is difficult to close just that component to fishing. A closure would need to be at a larger scale, e.g. the whole seagrass macro-habitat. However, meso-habitats will often provide the very specific target needed for restoration actions, such as enhancing penaeid fisheries production by focussing restoration on salt marsh edges (Minello et al. 2012). Even where management at the meso-habitat scale is not feasible meso-habitats play a vital role in management because awareness of the roles and functions of different meso-habitats is central to understanding the values of the macro-habitats they comprise to fisheries species.

Micro-habitats:

Micro-habitats are the smallest division of the hierarchy. They are sub-divisions of meso-habitats and play similar roles in understanding the relationships between habitats and fisheries species, but at a more precise scale. For instance, prop-root meso-habitats are comprised of micro-habitats such as bark, bark crevices, attached oysters and the spaces between roots. Micro-habitats are valuable for providing detailed understanding of the way meso- and macro-scale habitats are used, and so, although not amenable to direct management actions, they do contain information vital information to support management. Micro- and meso-habitat classification will be species and habitat dependent. For example, a mangrove jack can use the branch of a snag, but cannot use the bark of a branch. While *meso-* and *micro-habitats* contain information vital to management they represent the largest gaps in our current understanding.

3.6.2. Fish-habitat matrices

Fish-habitat matrices were constructed based on the four habitat axes conceptualisation and on information obtained by the different methods detailed above (Appendices 2-5). Each type of matrix relates fish to their habitats at one of the hierarchical scales appropriate for different levels of management.

Matrix 1: Process zone use by Australian fisheries species

At the first level, 'process zone' utilisation was evaluated for both juveniles and adults of 276 fishery species to produce a profile of process zone use by these two broad life-history stages. Fisheries lists (based on Taylor et al. (2012)'s Statewide Recreational Fishing Survey), Status Reports on commercial species from each Australia State, and species identified by the Game Fishing Association Australia were censused to identify the target set of fishery species. Where possible, process zone utilisation of juveniles and adults were determined based on published literature. Where this was not available or was ambiguous, information from FishBase (Froese and Pauly 2016) was used. Molluscs were not included because reliable life-history habitat use information was generally not available.

Current understanding suggests the gradient from freshwater to offshore waters can be conceptualised as comprising six identifiable *process zones*:

- ***Freshwater*** – areas of permanent freshwater;
- ***Transitional*** – the zone of semi-enclosed coastal systems between freshwater and estuary that alternates between the two conditions seasonally;
- ***Estuary*** – the downstream parts of semi-enclosed costal systems that are saline most of the year;
- ***Coastal*** – coasts, bays headlands and beaches;
- ***Inshore*** – inner areas of the continental shelf (including shallow-water reefs);
- ***Offshore*** – outer areas of the continental shelf and areas beyond the continental shelf.

Because both juveniles and adults tended to use more than one process zone, leading to an unmanageable number of *process zone utilisation patterns*, these patterns were summarised and distilled into a simplified set of Nursery and Adult profiles (Table 1), with categories indicating the range of process zones normally utilised by juveniles and adults. This resulted in 11 Nursery and 12 Adult profile categories:

Nursery categories:

- fresh – juveniles use freshwater and transitional nurseries;
- fresh-estuary – freshwater, transitional and estuarine nurseries;
- estuary – transitional and estuarine nurseries;
- estuary-coast – transitional, estuary and coastal nurseries;
- estuary-inshore – estuary, coastal and inshore nurseries;
- coastal – only coastal nurseries;
- coastal-inshore – only coastal and inshore nurseries;
- coastal-offshore – coastal, inshore and offshore;
- inshore – only inshore nurseries;
- inshore-offshore – inshore and offshore waters;
- offshore – only offshore nurseries.

Adult categories:

- fresh-coastal – adults use freshwater, transitional, estuarine and coastal areas;
- fresh-offshore – adults use freshwater, transitional, estuarine, coastal and inshore and offshore waters
- estuary – transitional and estuarine nurseries;
- estuary-coastal – adults use transitional, estuarine and coastal areas;
- estuary-inshore – adults use estuary, coastal and inshore areas;
- estuary-offshore – adults use estuarine, coastal, inshore and offshore areas;
- coastal-inshore – adults use coastal and inshore areas;
- coastal-offshore – adults use coastal, inshore and offshore areas;
- Inshore – adults only use inshore areas
- Inshore-offshore – adults use both inshore and offshore areas
- offshore – adults only use offshore areas.

Table 1. Summary of contractions of process zone categories into Nursery and Adult profiles

	Freshwater	Transitional wetlands	Estuary	Coasts, bays, headlands & beaches	Inshore (coastal) waters (incl. coral reefs)	Offshore waters	***Nursery profile***
JUVENILES	✓	✓					***Fresh***
	✓	✓	✓				***Fresh-estuary***
	✓	✓	✓	✓			
		✓					*Estuary*
		✓	✓				
		✓	✓	✓			*Estuary-coastal*
			✓	✓			
			✓	✓	✓		*Estuary-inshore*
			✓	✓	✓	✓	*Coastal*
				✓			
				✓	✓		
				✓	✓	✓	
					✓		*Inshore*
					✓	✓	Inshore-offshore
					✓	✓	*Offshore*
						✓	

	Freshwater	Transitional wetlands	Estuary	Coasts, bays, headlands & beaches	Inshore (coastal) waters (incl. coral reefs)	Offshore waters	***Adult profile***
ADULTS	✓	✓	✓				*Fresh-coastal*
	✓	✓	✓	✓			
	✓	✓	✓	✓	✓		
		✓	✓				*Estuary-coastal*
		✓	✓	✓			
			✓	✓			
		✓	✓	✓	✓		*Estuary inshore*
			✓	✓	✓		
			✓	✓	✓	✓	
				✓			*Coastal-inshore*
				✓	✓		
					✓		
				✓	✓	✓	*Coastal-offshore*
					✓	✓	
						✓	*Offshore*

Matrix 2: Process zone × macro-habitat matrix

At the second level, process zones were cross-classified with macro-habitat utilisation information to identify the range of macro-habitats that occurred in each process zone, in an Australian context (Fig. 3). The resulting process zone × macro-habitat template matrix was then populated with species-specific information. This was done for nine northern fisheries species that are commonly caught in estuaries and adjacent habitats (coastal marine and freshwater). These cover a range of size classes and trophic levels, and use habitats at different spatial scales. They included two invertebrate species, the banana prawns *Fenneropenaeus merguiensis* and the mud crabs *Scylla serrata*, and seven fish species, the detritivorous mullet *Chelon subviridis*, the planktivorous herring *Herklotsichthys castelnaui*, the meso-predators trevally *Caranx ignobilis*, mangrove jack *Lutjanus argentimaculatus,* barramundi *Lates calcarifer* and flathead *Platycephalus fuscus* (sedentary predator), as well as the apex predator bull shark *Carcharhinus leucas*.

The resulting matrices summarise the combinations of *macro-habitats* in particular *process zones* that are important at different life-history stages as well as key migration pathways, providing a simple graphical representation of the mosaic of known habitats and large-scale connectivities required by each species to complete its life history, it’s EHMC. Matrices can be broken down to indicate the particular sub-sets of the EHMC required by a particular component of the species population, such as the key nursery habitats. The reliability of information used in the matrices can be explicitly displayed by a representation of the uncertainty of each estimate, for example with the use of question marks.

Life-history categories considered in our matrices include settlement (or neonate stage for bull sharks), juvenile, sub-adult, adult and spawning stage (or, for the bull shark, pupping stage). ***Process zones*** and process zone sub-divisions considered for were: freshwater (subdivided into upland stream, lowland stream, floodplain fresh wetland); transition (subdivided into brackish/tidal wetland, estuary transition zone); estuary (subdivided into mangrove-lined channel and estuary mouth); coastal (subdivided into beach, headland, coastal reef, coastal zone, open water); inshore (subdivided into coral reef, island) and offshore subdivided into (inter-reefal, open ocean). In total, 24 **macro-habitats** were identified as important from the freshwater to the offshore environment, ranging from rapids in freshwater streams to seagrass beds in estuaries and subtidal rubble in the open ocean.

The matrix for each species therefore summarises all macro-habitat/process zone combinations that are important for the different life-history stages. Information on key migration pathways is also included, although the lack of published detail means this usually had to be assumed based on details of the macro-habitat/process zones utilisation. These matrices represent a simple graphical summary of the habitats and large-scale connectivities required by a species to complete its life history that can be directly utilised by managers.

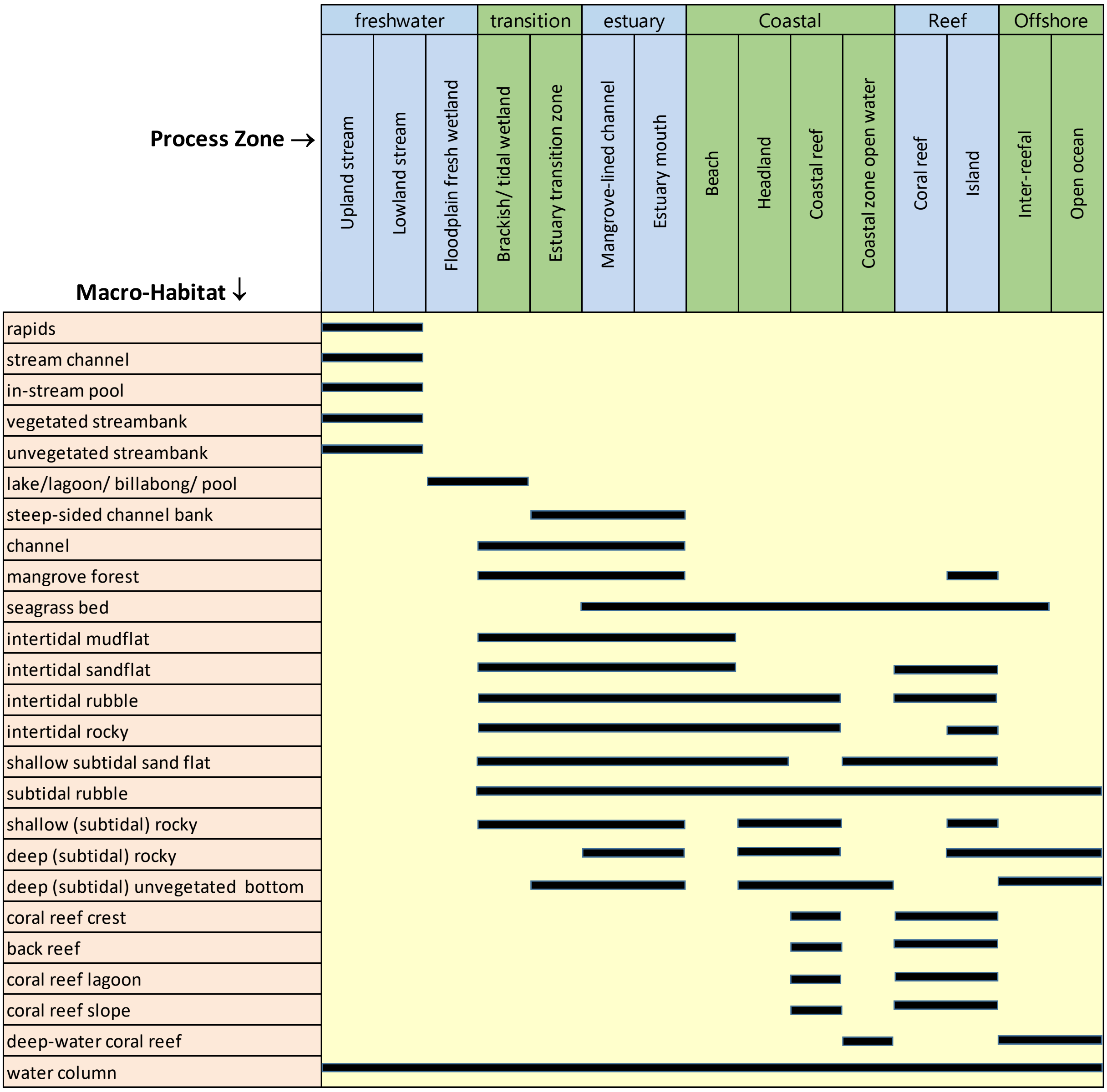

Figure 3. Conceptual matrix of the combination of the first two habitat axes from Fig. 1: process zone × macro-habitat, used as a template for the fish-habitat matrices. Black lines indicate the different habitats that occur in each process zone.

Matrix 3: Process zone × meso-habitat matrix

At the third level, we present a conceptual example of a meso-habitat matrix, developed for mangrove jack utilising meso-habitats within the mangrove-lined channel of the estuary process zone (Fig. 13).

The different matrices can be further developed, refined and updated as new information becomes available, to improve their utility as management tools.

4. Results and Discussion

Result and Discussion sections of the first components of this project (Objectives 1-5) can be found in Appendices 2-5. Here, we focus on the discussion on Objective 6, which summarises the information obtained throughout this study in a way that can be easily interpreted and used by different end users, including in management decisions.

4.1. Habitats in the context of fish life-history utilisation

The idea of fish habitat seems simple but in reality it is conceptually complex. For example, the term 'habitat' can be used to refer to things as different in spatial and conceptual scales as a whole estuary and a small patch of seagrass only a metre across. Different levels of 'habitat' have different relevancies to the question of utilisation by fisheries species and different relevancies to particular management questions. As a result, it is important to carefully define what is being dealt with when the term 'habitat' is used, and it is important that the definitions align with the systems of habitat attribution, the typologies and mapping used by key management agencies.

So, what is a habitat? What is considered to constitute a habitat varies greatly among studies (Ball et al. 2006). To quote Henderson's Dictionary of Biological Terms (2000), a habitat is "*the environment within which an organism is normally found. A habitat is characterised by the physical characteristics of the environment and/or the dominant vegetation or other stable biotic characteristics. Examples of habitats can be as general as lakes, woodland or soil, or more specific, such as mudflats or the bark of a tree."* Other definitions vary slightly, but it is generally agreed that a habitat is defined as the physical and chemical environment in which a species lives (Costello 2009). However, this is a generic 'minimal' definition (Jax 2006), and although such definitions can be useful to delimit classes of phenomena, they are difficult to apply because they lack a crucial element: the definition of scale that is needed to provide specific context. The lack of intuitive scale in these minimal definitions has led to the term 'habitat' being applied to units of disparate spatial and conceptual scales. For instance, in the marine environment, the term 'habitat' has been applied to entities as different in scale as the entire oceanic pelagic zone (Block et al. 2002) and the roots of a mangrove tree (Acosta and Butler IV 1997). The situation becomes even more confusing where a single habitat designation is used for units of quite different conceptual scales. For example, 'mangrove habitat' can refer to a tree (Duke et al. 1981), a stand (Verwey et al. 2006), a forest (Chong et al. 1990) or the entire mangrove system (Wolff et al. 2000) in which the 'mangrove habitats' at the smaller scales are embedded. These 'habitats' are all conceptually different, and organisms interact with each scale of habitat in a different way, so the functional links between organism and habitat are fundamentally different at each scale. Moreover, in general terms, ‘habitats’ are often poorly differentiated from other concepts, particularly “ecosystems”, even though the two are fundamentally different (Jax 2006), with ecosystems distinguished as functional ecological units defined by their biotic communities, and habitats as the abiotic environments in which they are embedded (Jax 2006, Costello 2009). The end result of such vague definition of what constitutes a ‘habitat’, is a term that means different things to different people, and so is open to miss-interpretation. Clearly, it is vital to have a coherent understanding of what is meant by the term ‘habitat’, with differentiated terminology for the conceptually different levels of ‘habitat’.

The importance of scale: Scale is important because it determines the way in which organisms interact with the ‘habitat’ and the ecological processes that are pertinent to that interaction (Morris 1987). For instance, a fish interacts with its estuary nursery ‘habitat’ at the scale of a particular phase of its life history (Levin and Stunz 2005), and interacts with a mussel bed ‘habitat’ where it feeds (Blasina et al. 2010) or a mangrove forest ‘habitat’ where it finds refuge (Laegdsgaard and Johnson 2001) at particular times of the day or tide. A variety of processes occurring over months and years (e.g. life-history migrations, season variations in nutrient delivery) are pertinent to the whole-of-estuary nursery ‘habitat’-animal relationship, while different process (e.g. tidal migration) are relevant to an organism accessing a feeding or refuge habitat. These different scales of animal-habitat interactions have inherently different levels of complexity and imply an intrinsic scaling of habitats. For example, the interaction of juvenile fish with the whole estuarine ‘habitat’ involves the interaction of many smaller scale ‘habitats’ that function in synergy to confer nursery ground value (Sheaves 2009, Nagelkerken et al. 2015). This nestedness of function could be taken to imply that every component of a system needs to be protected, but this is not reasonable or practical (Levin and Stunz 2005). Rather, a schema is needed that delineates these scales in a hierarchical way that facilitates the minimum set of components that comprise a species’ EHMC, relevant to a specific management objective, to be identified.

Requirements of a framework for identifying a species EHMC: A framework for identifying a species’ EHMC would need to (i) facilitate identification of EHMCs and the temporal scales at which they are utilised; (ii) align with components of standard hierarchical classification/mapping schemes to allow overlaying of EHMCs on spatial mapping to facilitate spatial prioritisation; and (iii) be adaptable for use by end-users with different needs and perspectives (e.g. managers, scientists, fishers, conservationists).

4.2. Fish-habitat matrices and their potential uses in informing management

4.2.1. Process zone use by Australian mobile fisheries species

Utilisation of “process zones” was evaluated for juveniles and adults of 276 fishery species to produce profiles of process zone use by the two life-history stages. This included 29 species of crustaceans, 197 species of teleosts, and 50 species of chondrichthyans (sharks, rays and chimeras). This information is summarised in Table A6-1 of Appendix 6. While by itself *process zone* information will usually be too broad for direct use in management, when combined with *macro-habitat* detail, *process zone* information is a key contributor to a simple management-support tool: the process zone × macro-habitat matrix.

4.2.2. Process zone × macro-habitat matrix

In most cases, habitat-based management can only effectively focus on the macro-habitat scale or above. However, by itself the macro-habitat scale does not provide a useful focus for management because it does not acknowledge the fact that mobile organisms like fish require a mosaic of habitats to conduct their life-history functions. A combination of macro-habitats embedded within particular process zones provides a more holistic conceptualisation of a specie's EHMC. Therefore, in this matrix, information of process zone utilisation is cross-classified with macro-habitat utilisation to produce *fish-habitat matrices*. This was done for nine important northern Australian coastal species (Figs. 4-12) to illustrate a simple process for identifying a species' EHMC.

For the mangrove jack, the matrix clearly shows that smaller individuals settle in a range of macro-habitats from the freshwater, transition and estuarine environments, including vegetated banks of lowland streams, mangrove forests, and inter- and subtidal rubble and rocky habitats (Fig. 8). They remain in these areas until the subadult stage, and use channels and unvegetated open bottoms as migration pathways to their adult habitats: headlands and coastal and inshore coral reefs and islands. Spawning occurs in reef slopes and in subtidal rocky habitats of inshore reefs and islands (Fig. 8). In contrast, flathead occupy similar habitats throughout their life-history (Fig. 9). They settle in estuarine intertidal and subtidal sandflats, and the following life-history stages later spread to occupy intertidal and subtidal unconsolidated substrates of the transition zone, estuaries and beaches (Fig. 9). Therefore, for the sustainability of this species, it is important to maintain the integrity of these unconsolidated substrate environments. It is however not known where flathead spawns or if they spawn in all habitats where they occur (Fig. 9).

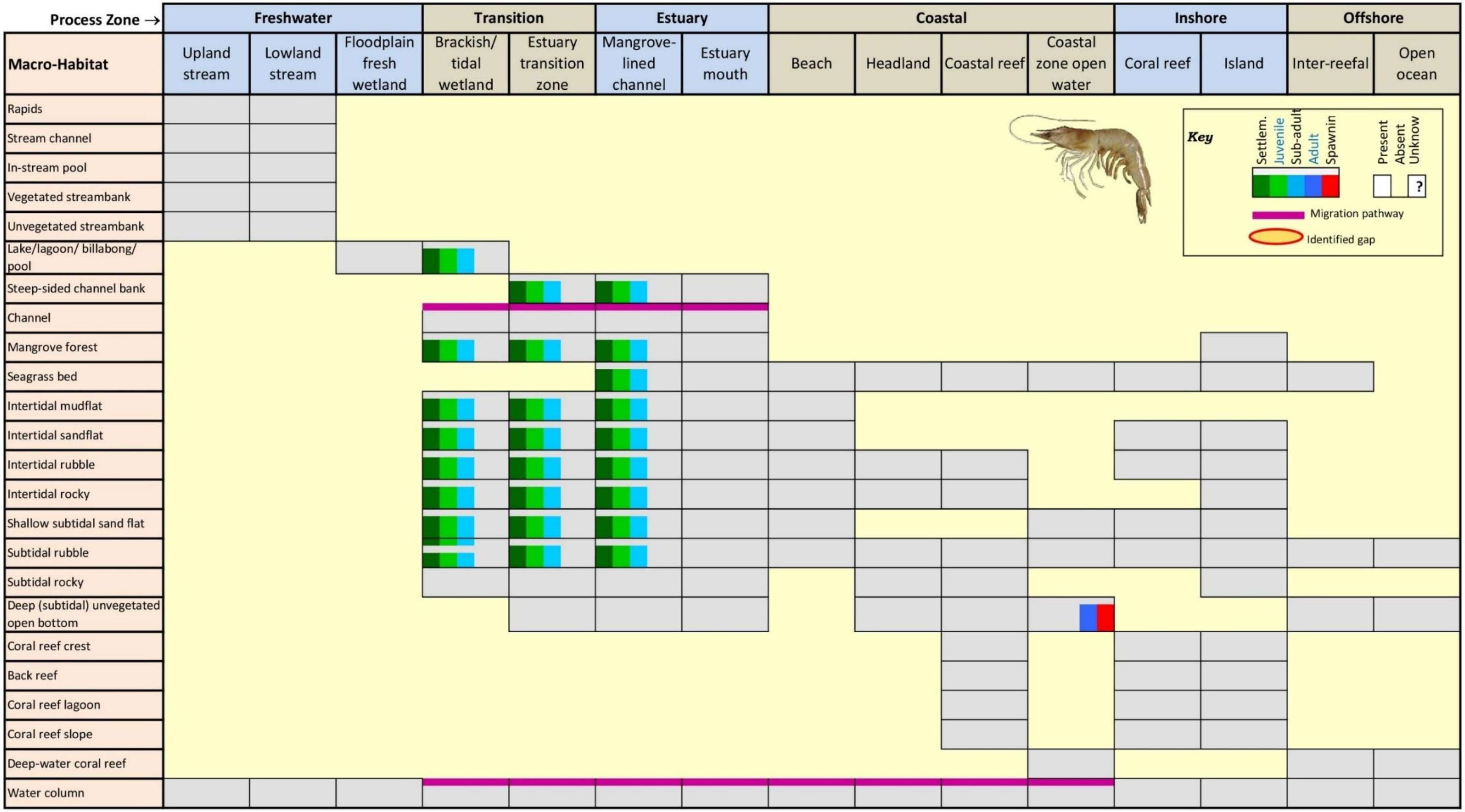

Figure 4. Fish-habitat matrix at the macro-habitat level for the banana prawn *Fenneropenaeus merguiensis*.

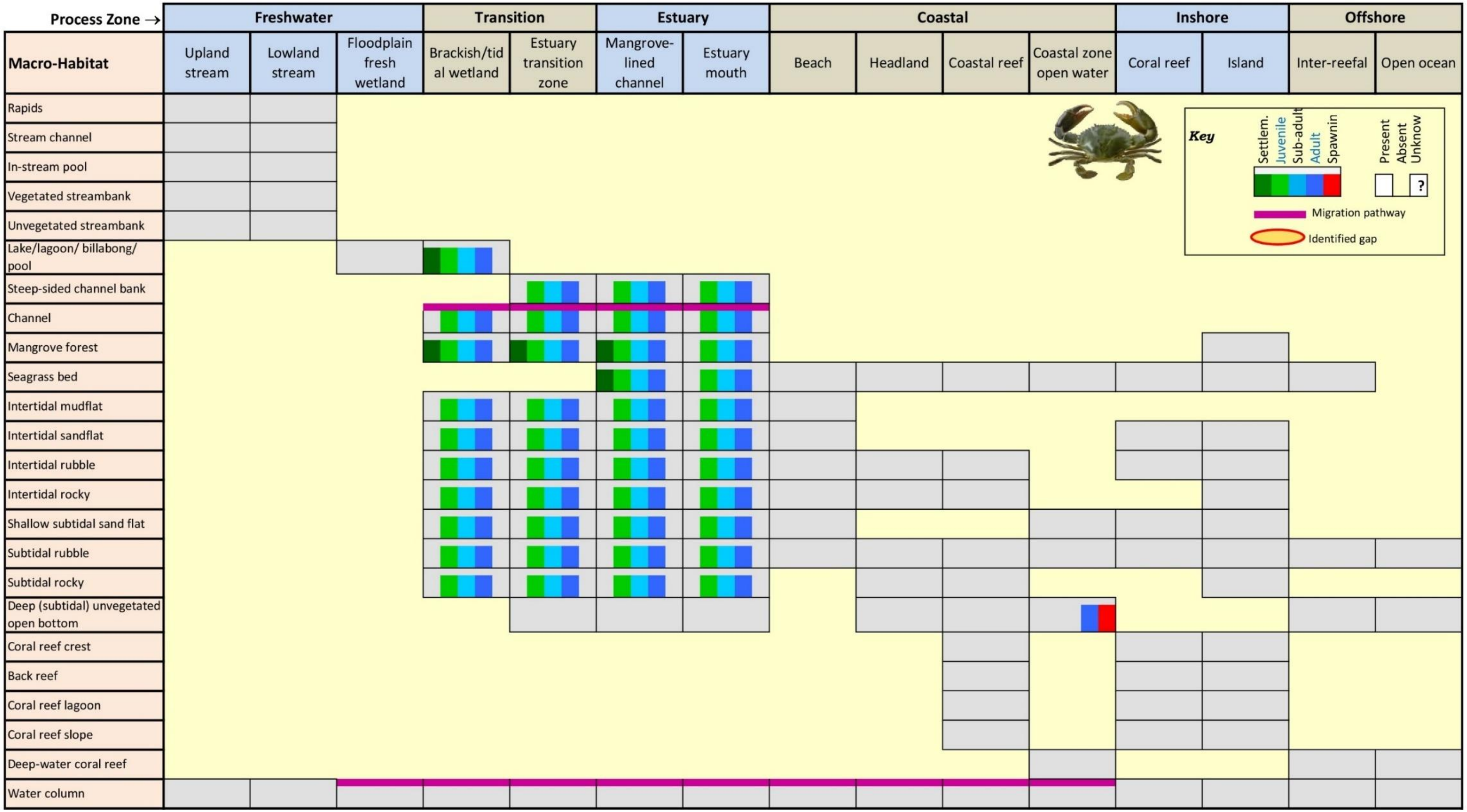

Figure 5. Fish-habitat matrix at the macro-habitat level for the mud crab *Scylla serrata*.

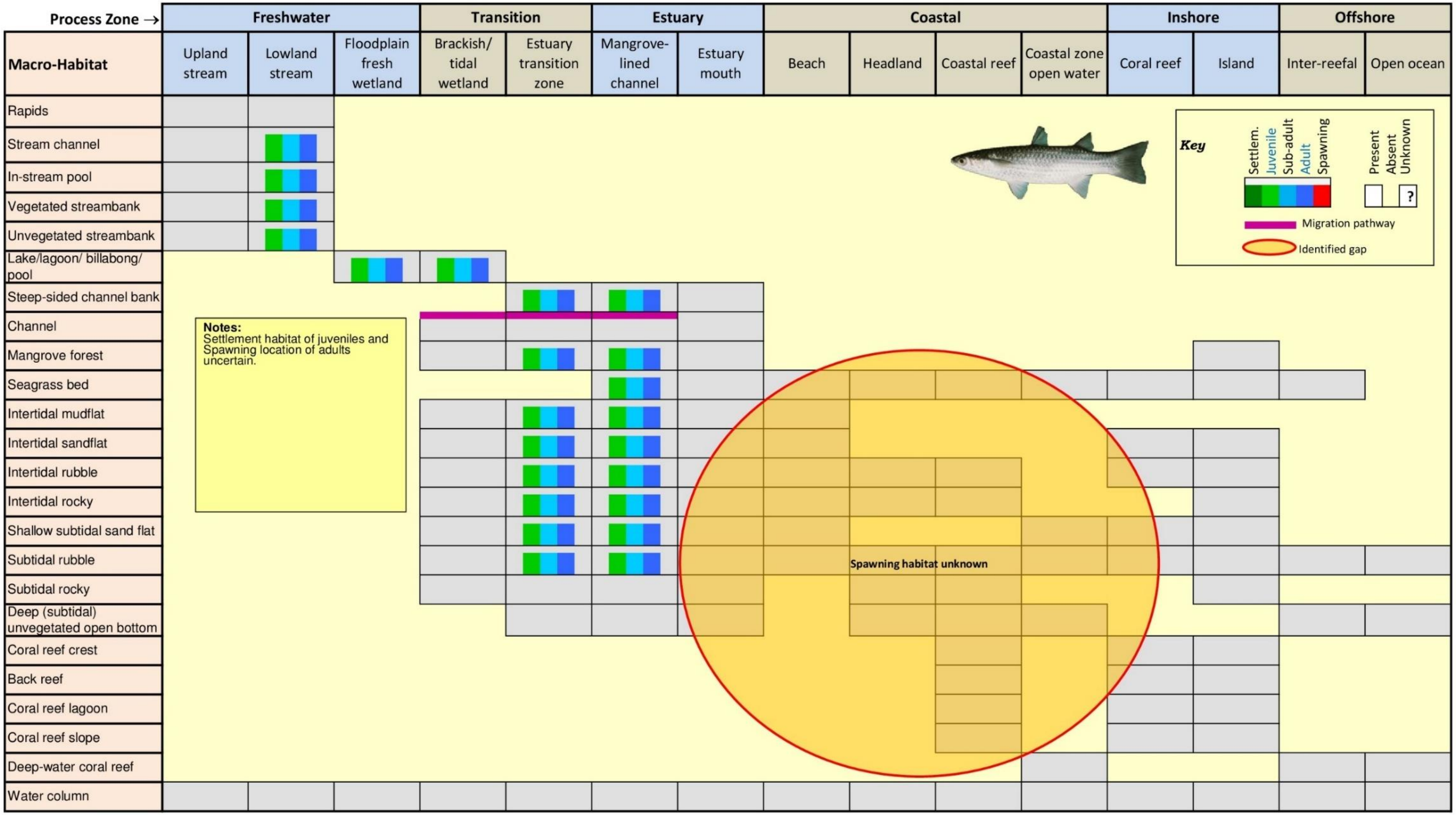

Figure 6. Fish-habitat matrix at the macro-habitat level for the mullet *Chelon subviridis*.

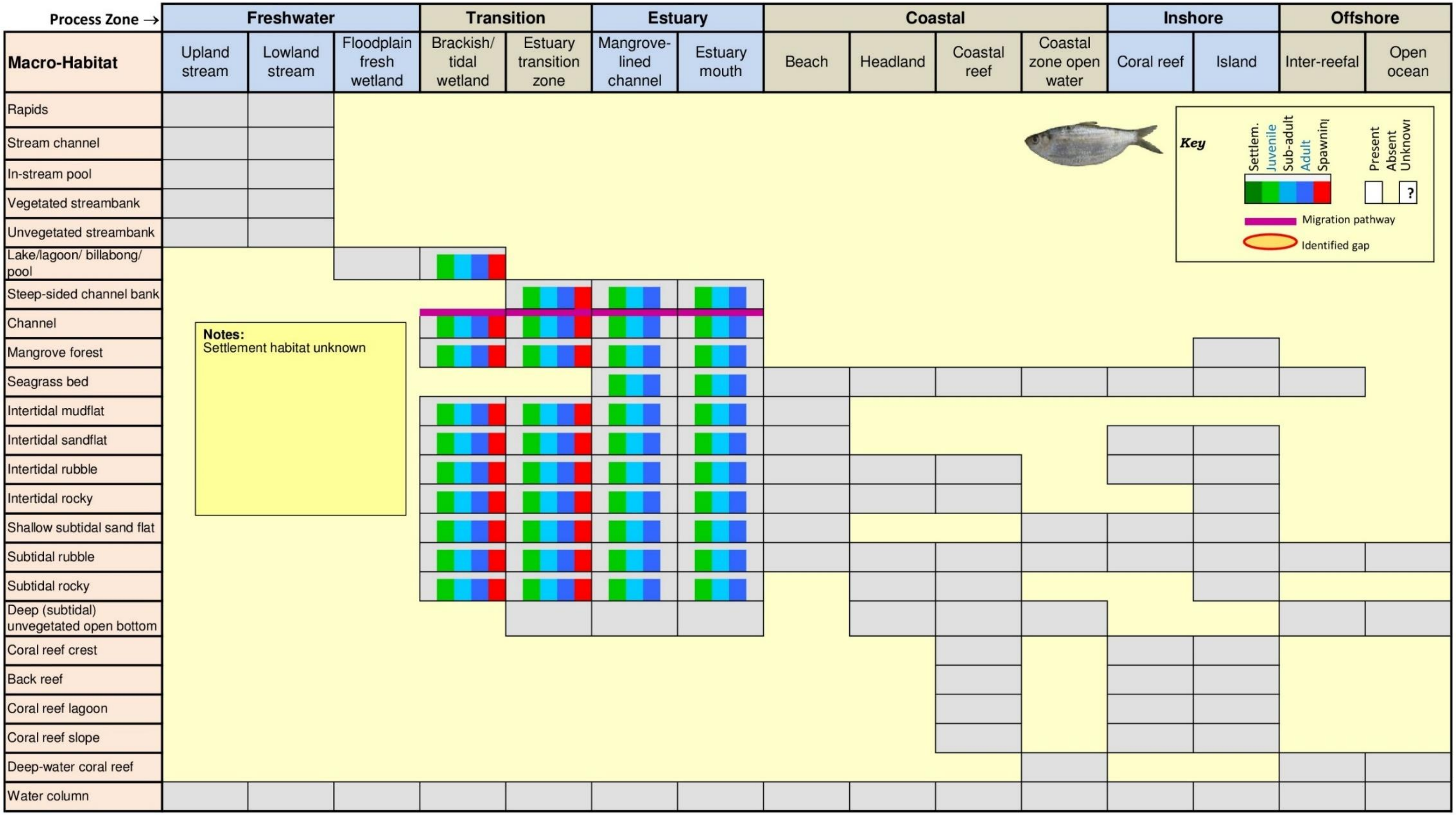

Figure 7. Fish-habitat matrix at the macro-habitat level for the herring *Herklotsichthys castelnaui*.

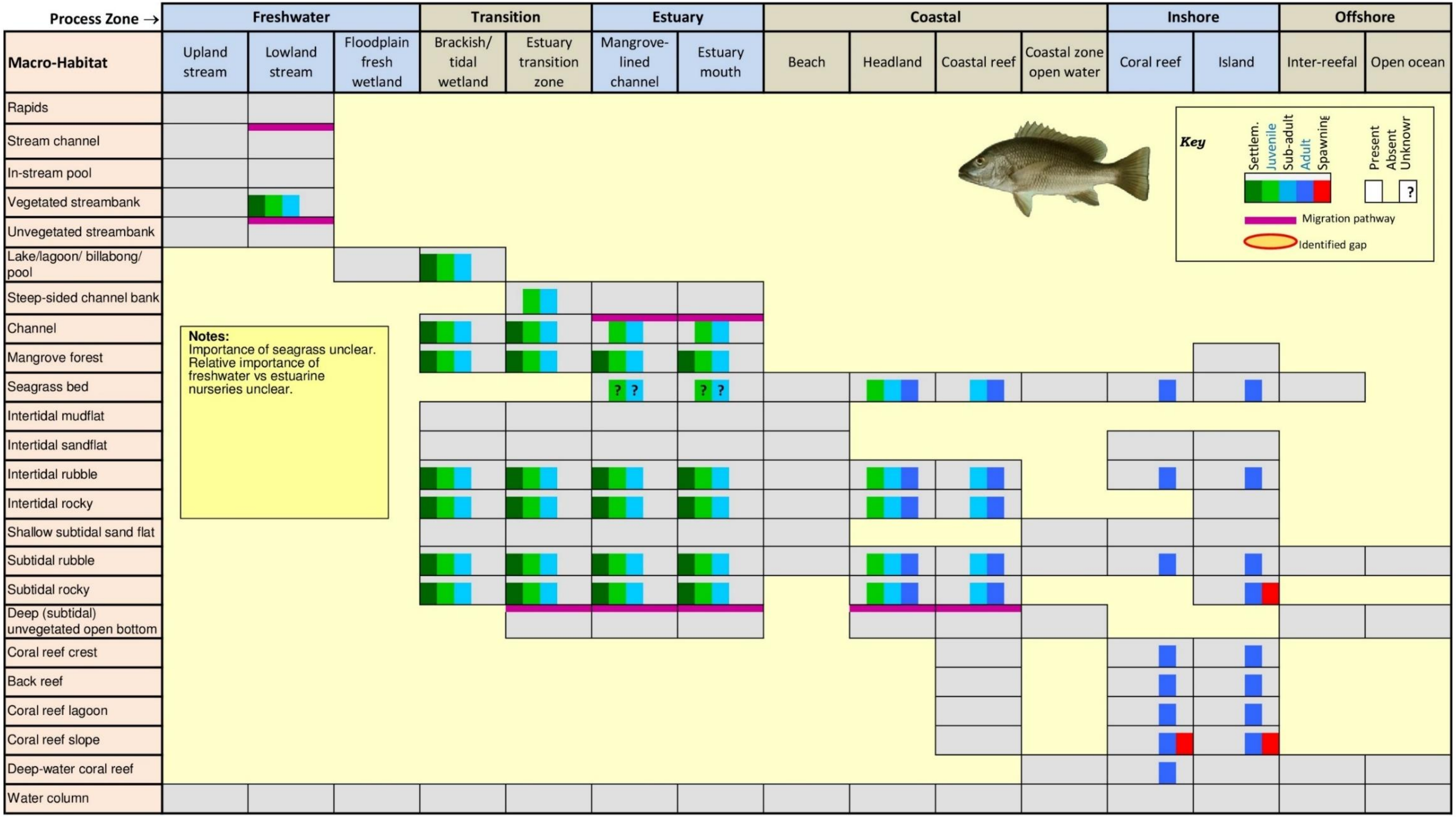

Figure 8. Fish-habitat matrix at the macro-habitat level for the mangrove jack *Lutjanus argentimaculatus*.

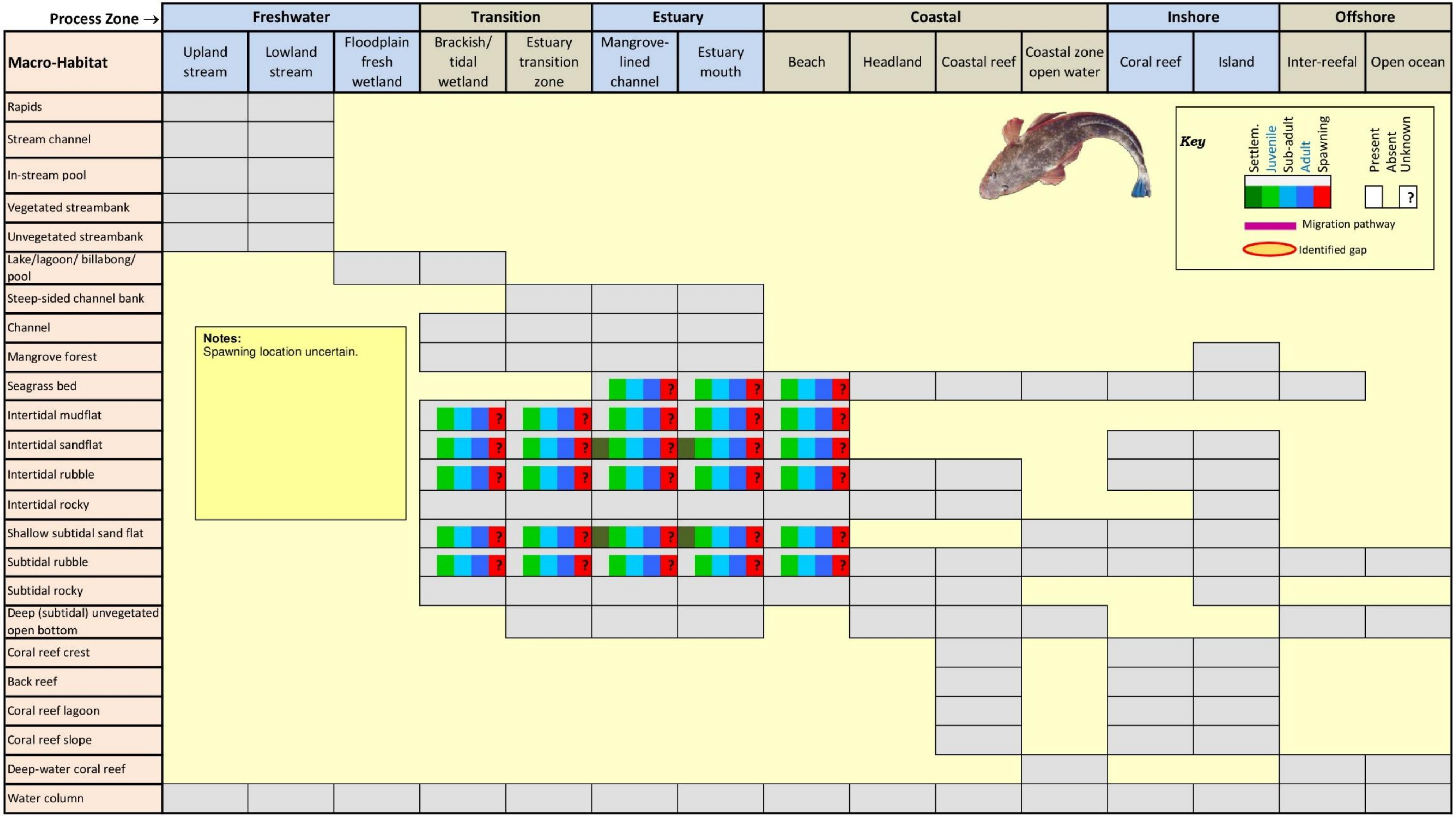

Figure 9. Fish-habitat matrix at the macro-habitat level for the flathead *Platycephalus fuscus*.

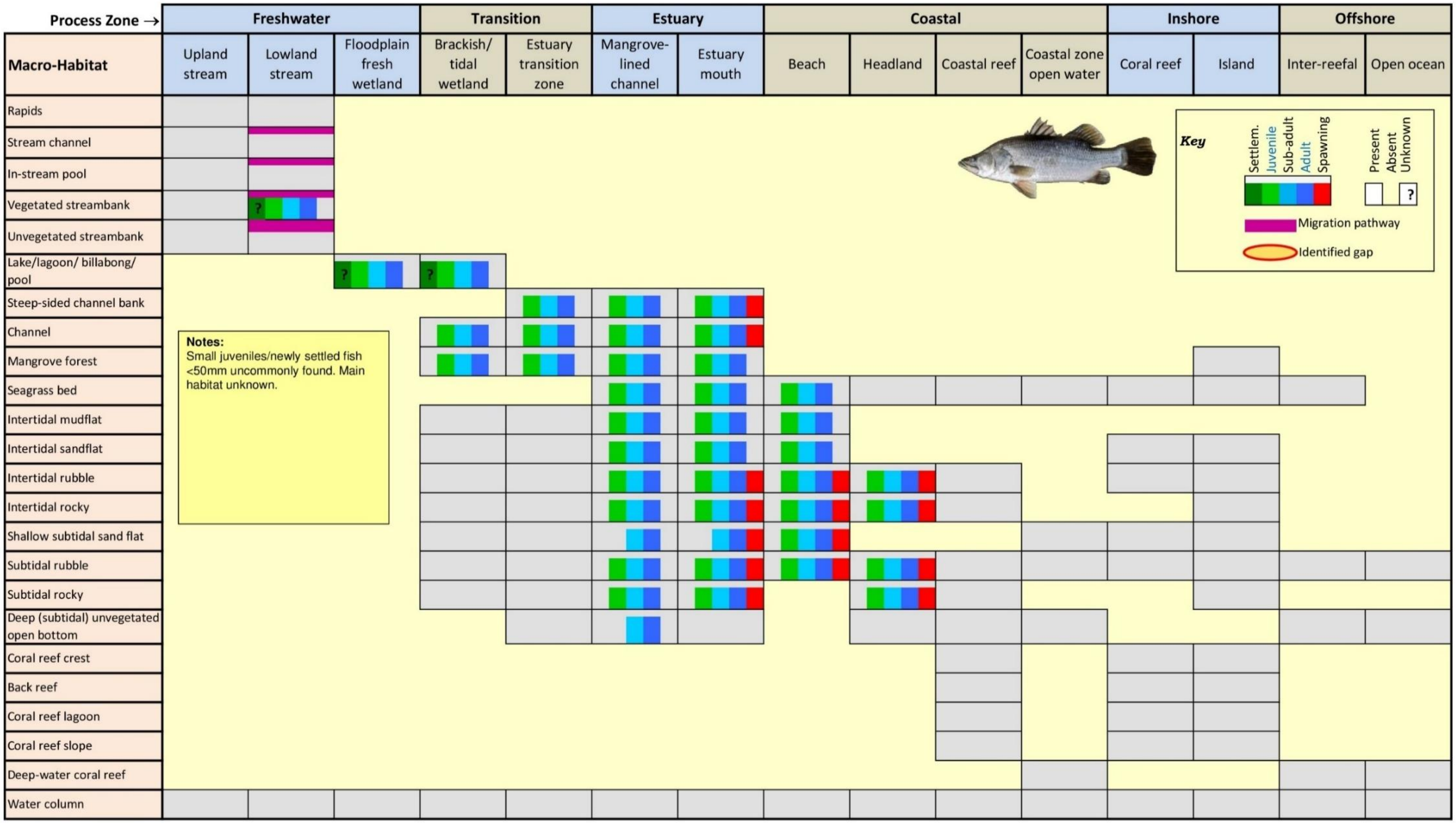

Figure 10. Fish-habitat matrix at the macro-habitat level for the barramundi *Lates calcarifer*.

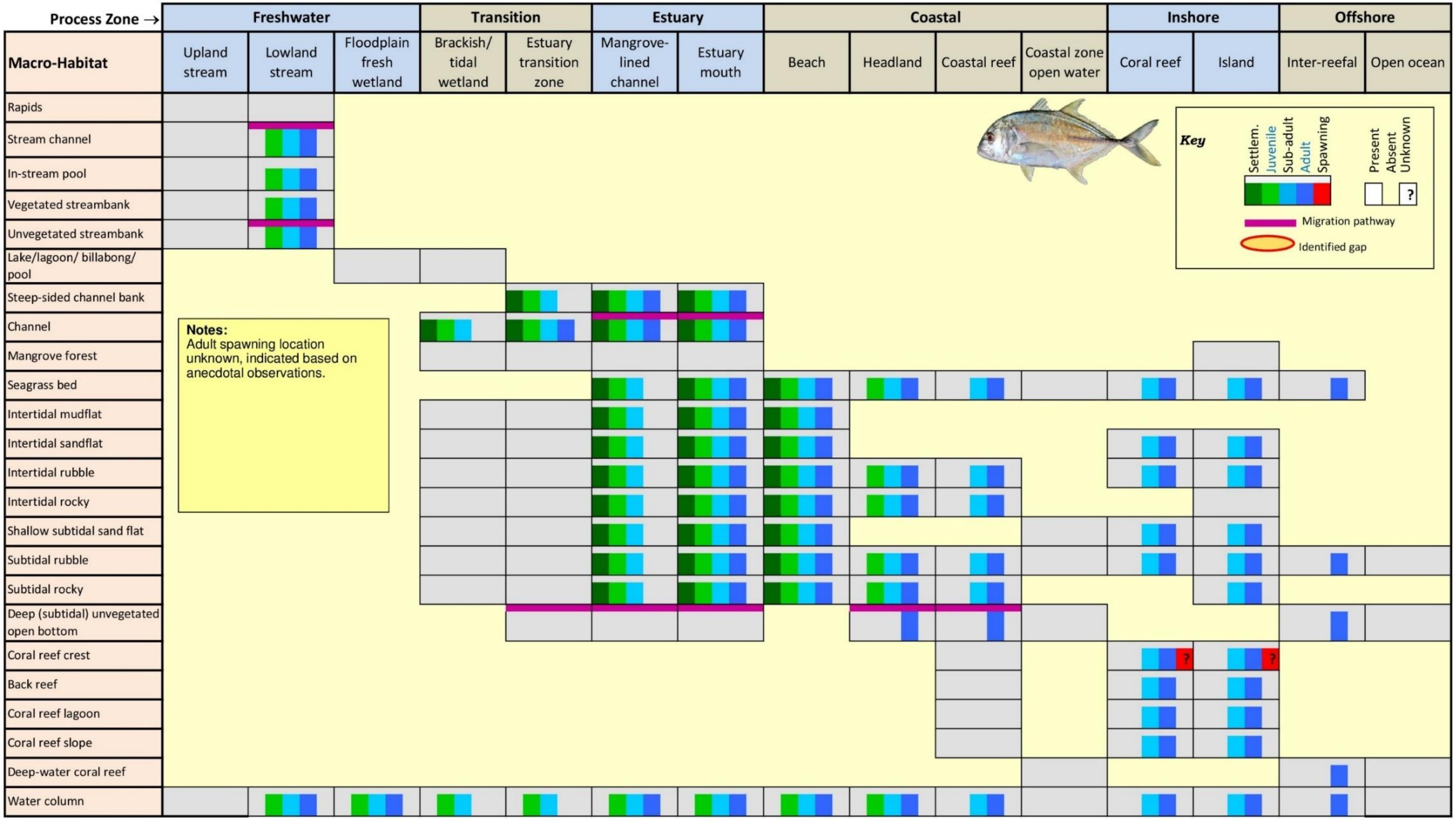

Figure 11. Fish-habitat matrix at the macro-habitat level for the trevally *Caranx ignobilis*.

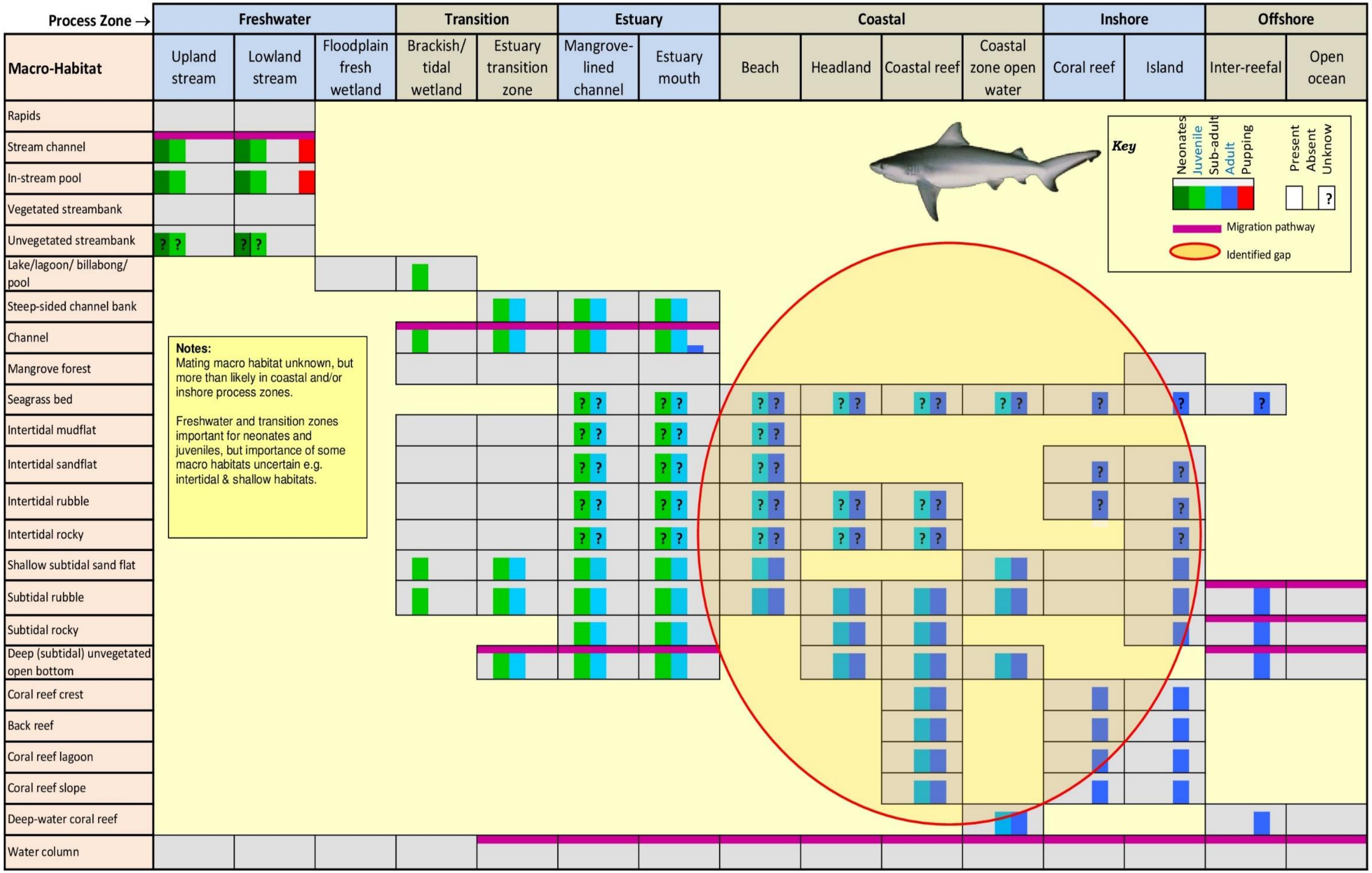

Figure 12. Fish-habitat matrix at the macro-habitat level for the bull shark *Charcarinus leucas*.

For banana prawns, larvae, juveniles and subadults all use all habitats in the transition zone and in mangrove-lined estuarine channels, with the exception of subtidal rocky areas and deep unvegetated habitats (Fig. 4). Channels are also used, but only as migration pathways. Adults occur in coastal open water habitats, where spawning also takes place (Fig. 4).

These examples illustrate the way that Process Zone × Macro-Habitat Matrices can provide a means of assembling a vast quantity of key data on life-history habitat utilisation into a logical and useful summary of the habitat requirements of a species, providing vital information in a format that is easily visualised and understood without the need for specialist knowledge.

4.2.3. Process zone × meso-habitat matrices

At a lower hierarchical level, the process zone × meso-habitat matrices can also provide valuable information for management. We present the example of a matrix for the mangrove jack using the different macro-habitats within a mangrove-line channel (Fig. 13). This matrix clearly shows the most important meso-habitats for this species, and how important the presence of structure is for this species. While areas void of structure (open sand/mud habitats, channels, open water with no discernible structure) are generally not used, structured habitats such as snags, mangrove roots and rubble are important meso-habitats for recruits, juveniles and subadults in mangrove-lined channels and associated macro-habitats (Fig. 13). In a management context, this indicates that it is important to preserve and protect the mangrove forest and riparian zone, so that vegetation can continually supply important structure to the estuarine systems. Indeed, snags are known to be important for a number of fish species, and this importance has resulted in a number of re-snagging programs (Roni et al. 2014). Any activities that involve clearing of riparian vegetation (e.g. construction, shipping or agriculture) need to take into account how the removal of snags and their sources affects these essential fish habitats (Roni et al. 2014).

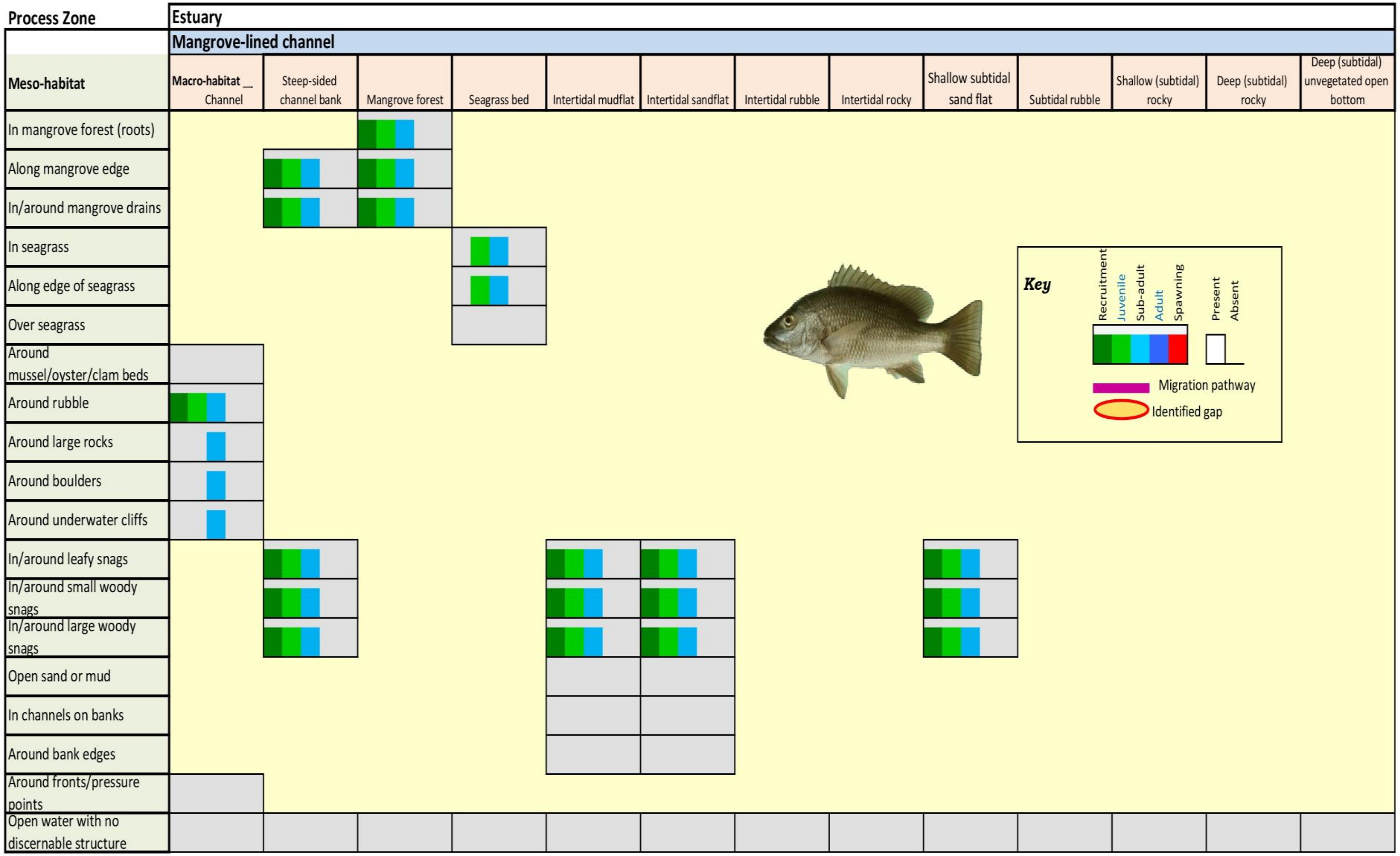

Figure 13. Process zone × meso-habitat matrix for the mangrove jack *Lutjanus argentimaculatus*.

4.3. Fish-habitat matrices as tools for management and conservation

Matrix tools, such as Process Zone × Macro-Habitat Matrices, provide a simple mechanism for assembling a vast quantity of key data on life-history habitat utilisation into a logical summary of the habitat requirements of a species. In doing so they providing a simple visualisation of the habitat needs of species that can be understood by specialists and non-specialists alike. Consequently, the matrices represent a streamlined tool for providing information of direct use to management. The ease of use of the matrices contrasts with more conventional modes of scientific reporting, such as via journal articles, which suffer from being difficult for non-specialists to understand and thus represent impediments to uptake and utilisation of knowledge, so representing a roadblock to effective management (Chapple et al. 2011).

One important feature of the Fish-Habitat Matrices is that they identify the habitats used by fish at different life-history stages in a hierarchical way. This allows identification of both the habitat unit that needs to be the focus for management (e.g. a macrohabitat) and the location where that habitat is utilised (i.e. the process zone). Consequently, rather than providing a simple list of the habitats used by a species, Fish-Habitat Matrices provide nuanced information that accounts for differential habitat utilisation during different life-history phases. This targeted information allows those using the Matrices to extract information that applies to scales that match both the boundary of the issue to be managed and the scale at which management can be implemented. This refinement is critical because, although failure to identify and protect a crucial component has potentially catastrophic consequences for fisheries (Mapstone et al. 2004), insufficiently detailed knowledge can force management to lock away unnecessarily large areas potentially impacting multiple user groups (Sutton and Tobin 2012), lead to well-known adverse effects of “blanket management” (Zhou et al. 2010), reduce fisheries production (Fletcher et al. 2015) or limit the chance of effective management due to poor targeting of habitat protection (Agardy et al. 2010).

The level of detail gathered from using a macro-habitat framework represents a win-win situation for all stakeholders. For instance, the matrices can assist in developing more accurate estimates of the extent and nature of impacts from habitat loss as a result of particular actions (e.g. they can help gauge which species are likely to be the most affected by certain impacts), and ultimately provide the information needed by managers to support decisions on zoning and development. Also, development offsets can be directed in a more effective way than is currently possible, e.g. offsets can be directed to the rehabilitation of particular damaged habitats so that benefits to fisheries species are maximised. Below, we discuss some examples of how these matrices can be used in informing management and conservation.

In addition, it provides a display on which knowledge gaps can be explicitly identified. Consequently, Fish-Habitat Matrices have particular relevance to decision-making because they allow precise identification of the specific macro-habitats used by target species in the different process zones across life-history while ensuring that uncertainty is acknowledged.

4.3.1 Assessment of relative habitat values

The evaluation of the 'habitat' requirements of Australian fisheries species at even the coarsest (*process zone*) scale provides important insights. Analysis of the data from Table A6-1 (Appendix 6), on *process zone* utilisation by juvenile and adult fisheries species, shows that estuarine, coastal and inshore nurseries contribute most species (77%) to the major estuary/coastal/inshore fisheries, with the largest contribution (44%) by juveniles that use both estuarine and coastal nurseries (Fig. 14). This indicates that the estuarine and coastal areas act as components of an interrelated nursery mosaic for many species, with different nursery values often contributed by many different macro-habitat components (Nagelkerken et al. 2015), underlining the importance of the whole interacting mosaic and the connections among its components (Sheaves 2009). A substantial component of species in the coastal/inshore fisheries use only coastal nursery areas, emphasising the danger of assuming all inshore species utilise the same nursery areas, and highlighting the danger of conducting large scale works (e.g. dredging, spoil disposal) in coastal areas without a complete understanding of the fisheries and life-history values of these areas (Grech et al. 2013). Species in offshore fisheries mainly use offshore (60%) or coastal (19%) nursery areas. This information is broken up by major fisheries taxonomic groups in Table 2.

At a smaller scale, process zone × macro-habitat matrices can be used to help identify the main habitats to preserve for the sustainability of the different fisheries. For example, barramundi moves from freshwater to the estuary process zone with ontogeny (Fig. 10). Although not much published information is available on small, recently settled juveniles, available knowledge suggests that these use vegetated banks of lowland streams and freshwater and brackish pools and billabongs (Fig. 10). These habitats and their connectivities should therefore be protected to ensure the continuing recruitment of barramundi into the exploited stages, therefore ensuring the sustainability of the fisheries. Herrings only use the transition and estuarine process zones, but use most macro-habitats within those zones at all life stages (note that settlement habitats are however unknown) (Fig. 7), suggesting that there is no specific macro-habitat that should receive special attention for preserving this species, and that, if needed, protection at process zone level would be appropriate. For the mullet, settlement and spawning habitats are unknown, but juveniles, subadults and adults use a range of habitats from freshwater lowland streams to pools, lagoons and billabongs fresh and brackish wetlands and various macro-habitats in the estuarine transition zone and mangrove-line channels (Fig. 6), so there is no particular habitat that management can focus on to protect a mullet fishery. Mud crabs seem to use a range of habitats in transition and estuarine process zones and use channels as migration pathways, but the settlement stage seems to occur mostly in brackish pools, mangrove forests and in seagrass beds in mangrove-lined channels (Fig. 5). These settlement habitats seem particularly important for the mud crab fishery. Adults use open water habitats, and these habitats are also used for spawning (Fig. 5).

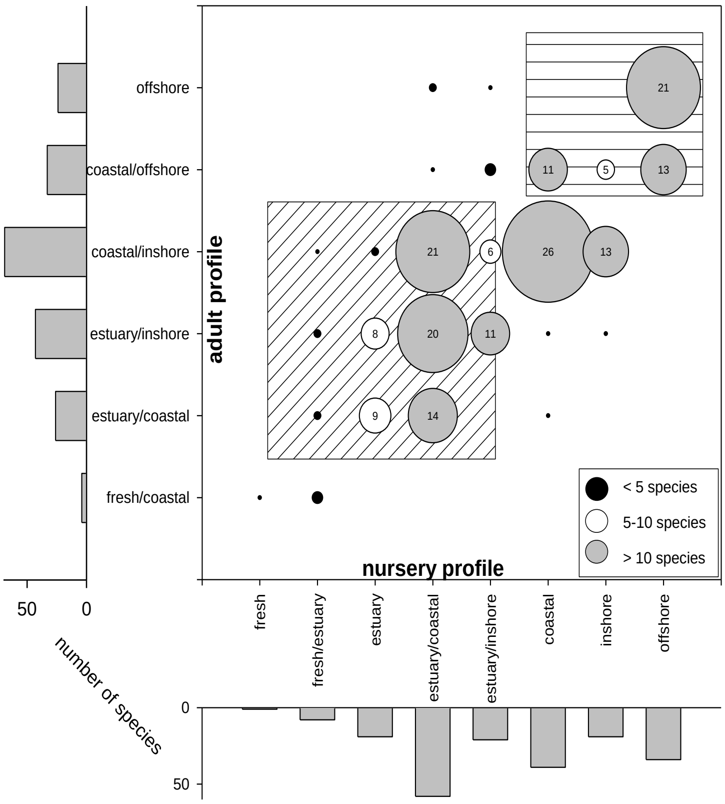

Figure 14. Contribution of juveniles from different nursery categories to adult stocks. Histograms indicate the number of species in each profile category; bubbles indicate the number of species from each nursery profile category contributing to each adult profile category (numbers indicated for bubbles with 5 or more species. Cross hatching indicates the major estuarine, coastal water and inshore fisheries; horizontal hatching indicates offshore fisheries.

In Table 3, we present further examples on how the process zone × macro-habitat matrices can be used, while considering the nine species for which these matrices were built. In the first scenario, we aim to predict the effects of removing a mangrove forest to build a structure. Three of the nine species (mangrove jack, banana prawn and mud crab) would lose key nursery habitats, and two other species (barramundi and herring) could be minimally affected (Table 3). Given their habitat requirements, the remaining four species (mullet, flathead, trevally and bull shark) would probably not suffer negative impacts from such development. This type of information can also be used to determine the best offset action to implement. For example, if a mangrove forest was to be protected or planted to offset a development, the key habitats of three important species, the mangrove jack, banana prawn and mud crab, would be preserved/created meaning that this offset action could lead to positive outcomes for their fisheries. Scenario 2 takes a species-specific approach, where the aim is to improve banana prawn and mangrove jack fisheries. For both species, the matrices give information on the key macro-habitats that should be the focus of management actions. Management can also target specific life stages, if appropriate, e.g. to protect spawners. In scenario 3, we present an example of the impacts of connectivity loss by the construction of a road or bund wall that severely restricts river flow into the estuary and adjacent coastal area. Two species, the barramundi and bull sharks, would be highly affected due to the freshwater habitat requirements of juveniles, and this action could also have a small effect on mullet, trevally and mangrove jack (Table 3).

Table 2. Summary of numbers of species of crustaceans, teleosts and condrichthyans in aggregated nursery and adult profile categories.

Profile	Nursery			Adult		
	Crustacean	Teleost	Condrichthys	Crustacean	Teleost	Condrichthys
Coastal	5	9	13	0	2	0
Coastal inshore	5	24	13	15	64	11
Coastal offshore	0	4	3	7	19	20
Estuary	7	18	0	0	4	0
Estuary coastal	7	57	4	0	31	0
Estuary inshore	4	18	4	6	44	5
Estuary offshore	0	0	0	0	1	2
Fresh	0	1	0	0	0	0
Fresh estuary	0	7	1	0	0	0
Fresh coastal	0	0	0	0	3	0
Fresh offshore	0	0	0	0	0	1
Inshore	1	22	3	0	6	2
Inshore offshore	0	9	4	0	6	8
Offshore	0	20	4	1	17	1

Table 3. Fish-habitat matrices as a management tool: using the matrices for the nine key tropical species (Figs. 4-12) to present habitat value scenarios and evaluate potential outcomes and most appropriate conservation/offset actions.

Scenario	Species affected	Probable outcome/appropriate action
1. Removal of mangrove forest to build a structure	Mangrove jack Banana prawn Mud crab	Loss of key nursery habitat for mangrove jack, banana prawn and mud crab Loss of key habitat for all life stages of mud crab
	Barramundi Herring	Minimal effect on barramundi and herring, as they use an array of other macro-habitats
1. Species-specific: - improve banana prawn fishery	Banana prawn	Management/protection of mangrove forest and intertidal mud flats in transitional and estuary process zones would benefit prawn recruits, juveniles and subadults. Adults would benefit from protecting deep unvegetated open bottom habitat in coastal open water areas.
- improve mangrove jack fishery	Mangrove jack	Management/protection of mangrove, rubble and rocky macro habitats in transitional and estuary process zones would be beneficial for early life stages. Extension of management plans to rubble and rocky habitats in coastal and inshore zones would be beneficial for sub adults and adults. Management/protection of coral reefs important for adults and spawning.
3. Restricting connectivity between a river and the estuary/coast, e.g. by construction of a bund wall, roads.	Mullet Trevally	Will prevent mullet and trevally moving into upper ranges, but probably have little effect on these species.
	Mangrove jack	Mangrove jack's upper habitat limit would be disrupted, but minimal when considering overall habitat use, e.g. several other macro-habitats in transitional and estuaries zones are important for recruits and juveniles.
	Barramundi	Barramundi would be highly affected, mostly by restricting movement between fresh and saltwater for spawning, and possibly affect settling or recruits in upstream habitats.
	Bull shark	Bull shark would be highly affected by the loss of connectivity between pupping/nursery areas and adult habitats

5. Implications

At the most basic level, the outputs of this project allow the values of fisheries habitats to be assessed, helping ensure decision makers understand the benefits of habitats, how to minimise impacts and the best ways to develop realistic offsets. Its significance is likely to be substantial but because the utilisation of particular habitats throughout the life-cycle of most species is unknown, estimates of benefits need to come by way of example. For instance, loss of connectivity to key habitats has contributed to reductions in catches in Coorong - Murray Mouth fishery to well below 50% of historic levels and even modest repair to habitats (20% gains) is estimated to be worth $5.7M per annum (Brookes et al. 2015).

The understanding gained in this project benefits commercial, recreational and indigenous fisheries, as well as Australian seafood consumers, by providing managers in organisations like the Great Barrier Reef Marine Park Authority (GBRMPA), Queensland Department of Agriculture and Fisheries (QDAF) and the North Territory Department of Resources (Fisheries), with the information needed to make strategic decisions that rely on understanding the relative values of different habitats to coastal and estuarine fisheries species. Potential impacts include improved management practices, reduced risk to resources and the ability to target habitat repair actions appropriately, therefore enhancing resource sustainability. This work also provides the information needed to populate coastal habitat maps and classification schemes that in turn will be key contributors to improved management outcomes. For example, they can be useful to facilitate the development of specific metrics for the quantification of the fisheries benefits stemming from habitat repair.

Additional outputs will value-add to DAFF, GBRMPA and EHP habitat mapping programs by providing the information needed to populate their habitat maps with a "fisheries habitat value" layer. The fish/habitat information will also provide the necessary basis for Threat and Risk Maps that can be developed in conjunction with end-users like GBRMPA, QDAFF and EHP, to enhance their abilities to assess location-specific risks, set risk reduction targets, and make improved decisions on development applications and offsets.

5.1 Fish Habitat Matrices

The main output of this study are the Fish-Habitat Matrices that summarise the available fish-habitat understanding for the different like stages of key fisheries species. These Matrices represent much needed information to support decisions on zoning and development and to more efficiently manage offsets. The Matrices provide fish-habitat usage detail defined at a hierarchy of scales. This allows those using the Matrices to extract information that applies to scales that match both the boundary of the issue to be managed and the scale at which management can be implemented.

The Matrices allow assessment of which habitat assets are most vital to conserve and which are most vital to replace or remediate, enabling more accurate estimates of the extent and nature of habitat loss as a result of particular actions, and determine the type and extent of offsets required. In addition, Fish-Habitat Matrices provide a way to display knowledge gaps, enabling uncertainties to be explicitly considered. Consequently, Fish-Habitat Matrices can be used as a basis for strategic prioritisation and decision making to direct management actions such as determining the optimal siting of developments to minimise adverse impacts on fisheries habitats and values; directing the development of coastal infrastructure in ways that enhance, rather than degrade, fisheries habitat values; and directing environmental offsets to the repair and revitalisation of degraded habitats to optimise their benefits to fisheries. The improved targeting the Matrices allow represents a win-win situation across stakeholder groups: managers will be able to make decisions more rapidly and with more certainty; developers' offset money can be more accurately and effectively directed; key fisheries habitats can be protected more effectively without the need to lock away productive fishing areas by unnecessary zoning; and the success of offsets will increase improving harmonious relations among stakeholder groups.

6. Recommendations

Fish-Habitat Matrices have the potential to be valuable tools for both fisheries management as well as broader ecosystem management. However, the matrices developed are only examples specific to north-east Queensland coastal and estuarine waters. The complex and location specific nature of fish-habitat relationships, and the substantial body of information needed as input into the Fish-Habitat Matrices mean that additional work is needed to operationalise the approach.

6.1 Further development

Future development will require 3 steps:

1. Developing a standard approach for capturing, assessing and integrating diverse sources of information for incorporation into the Fish-Habitat Matrices. Here, substantial development effort will be required. However, there are useful models that could be adapted to this purpose. One of the most likely would be an adaptation of the approach used in developing and implementing the Queensland Wetlands Programs *Wetland Prioritisation Decision Support System for the Great Barrier Reef Catchment* (WPDSS) (QWP 2016), a key tool for decision support for optimal prioritisation of restoration and protection actions widely utilised by the Queensland Department of Environment and

Heritage Protection (EHP) and the Great Barrier Reef Marine Park Authority (GBRMPA).
2. Working with multiple end-users to test, check, evaluate and update the methodology.
3. Developing substantive studies to prioritise information needs and conduct the multidimensional studies need to populate the Fish-Habitat Matrices.

7. Extension and Adoption

The key knowledge output of the project is an integrated understanding of the habitats required by key fisheries species across their life-histories and the connectivities between those habitats. This knowledge is presented as matrices cross-correlating habitat and life-history phase for the most important commercial and recreational species. Target audiences include all end users, particularly those charged with managing fisheries, coastal ecosystems and coastal ecosystem resources (e.g. Great Barrier Reef Marine Park Authority (GBRMPA), Queensland Department of Agriculture Fisheries (QDAF), Northern Territory Department of Primary Industries and Fisheries (NT DPIF), Queensland Department of Environment and Heritage Protection (EHP), Queensland Wetlands Program (QWP), Local Councils, and Natural Resource Managers (NRMs) including Terrain, NQ Dry Tropics, and Reef Catchments). In addition, they represent a key resource for those assessing potential environmental impacts. The Fish-Habitat Matrices and associated documentation have been reviewed by managers from EHP and GBRMPA, and used to underpin research in the National Environmental Science Programme (NESP) Marine Biodiversity Hub Project B4 - *Underpinning the repair and conservation of Australia's threatened coastal-marine habitats*, a project aimed at scaling-up of repair efforts for coastal ecosystems. The Fish-Habitat Matrices are also being used as a key input to support the *Global Tropics Future Project* that focuses on Science, Technology, Engineering and Mathematics (STEM) engagement for Queensland school students.

The project has already resulted in the publication of two scientific papers with three more in review or advanced stages of preparation (see below).

More extensive uptake will require on-going development to operationalize the frameworks and tools developed here (see 6. Recommendations).

Project materials developed

Scientific Outputs

Scientific articles published:

1. Abrantes K, Barnett A, Baker R, Sheaves M (2015) Habitat-specific food webs and trophic interactions supporting Australia's coastal-dependent fishery species. Reviews in Fish Biology and Fisheries 25:337-363

2. Sheaves M, Johnston R, Baker R (2016) Use of mangroves by fish: new insights from in-forest videos. MEPS 549: 167-182

Scientific articles submitted:

1. Bradley M, Baker R, Sheaves M (submitted 01/07/16) Hidden components in tropical seascapes: Deep-estuary habitats support unique fish assemblages. MEPS

2. Sheaves M, Johnston R, Bradley M (submitted) New insights into fish use of mangroves and nursery value. *Fish and Fisheries*.

Scientific articles in Preparation:

1. Sheaves M, Developing habitat matrices as tools for identifying and managing essential fish habitats - This paper is based on the development of the habitat matrices and is in advanced stage of preparation.

Note also that material from Appendices 2 to 5 will soon be formatted to be submitted for publication.

APPENDICES

Appendix 1. References

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Appendix 2. Critical Fisheries Habitat: Developing Detailed Models of Life-History Habitat Utilization Via Large-Scale Video Analysis

Michael Bradley and Marcus Sheaves

Executive Summary

Coastal ecosystems such as estuaries are highly valuable for fisheries production, but the mechanisms underpinning the generation of this value, and the roles that different habitats play in this process, remain unclear. The objective of this study was to develop detailed models of the life history stage-specific habitat utilisation of key coastal and estuarine fisheries species at the most

detailed measurative level possible. Focused on the fish habitat protection area of the Hinchinbrook region, cutting edge underwater video sampling methods were combined with new statistical techniques to provide the latest ‘best practice’ model of fisheries habitat. Three years of sampling uncovered life-history specific habitat utilisation patterns for many fisheries species, new and important habitat types, and intricate links between habitats in support of fisheries.

Habitat types varied in their value for different species, and whether a habitat occurs in a coastal embayment, a tidal creek or upstream, can change the species that use it and how much it is used. Areas of structural complexity, particularly woody debris, were valuable to a wide variety of species. Woody debris in these systems is best viewed as a continuation of mangrove habitat into the subtidal realm, where it also serves as habitat for subtidal species. Previously overlooked rock habitats in the upstream, creek and embayment process zones also emerged as highly utilised by coastal fauna. Combinations of habitats appear to be important in supporting different taxa, with strong links between habitats apparent for many fisheries species, and ontogenetic habitat shifts particularly important. We found clear distinctions between early juvenile and late juvenile habitat use patterns. In general, early juveniles appeared to be concentrated in a single habitat type, while late juveniles were more evenly spread between three or four habitats. In addition, there was clear partitioning between the early juveniles of different Lutjanus, Lethrinus and Acanthopagrus species. This ontogenetic progression of highly specific early juvenile habitat to more general late juvenile habitat, in general, appears to flow downstream through one or more process zones. Habitat diversity, and in particular structured habitat diversity throughout different parts of the coastal zone (in a coastal embayments, tidal creeks or upstream reaches), appears particularly important in maintaining the fisheries values of coastal ecosystems. Therefore, to maintain function, it is critical to maintain the breadth of naturally occurring habitat types, as well as passage between them.

1. Introduction

Although coastal ecosystems are valuable contributors to fisheries production around the world (Costanza et al. 1997), the mechanisms that generate this value, and the roles that different habitats play in this process, remain unclear. At the ecosystem level, there is evidence that coastal environments support fisheries production (Manson et al. 2005, Meynecke et al. 2008). At the habitat level however, there is little understanding of what constitutes a valuable fisheries habitat (Sheaves 2006). In fact, nursery grounds have been identified in detail for very few Australian inshore fisheries species, and often there is no comprehensive information about the range of habitats occupied or their relative importance. Critically, there is almost no information about the first habitats used by small juveniles of most fisheries species.

This lack of detailed habitat level information makes it difficult to precisely manage these systems. Individual habitat level relationships can be critical in supporting fish populations, meaning that determining these relationships is crucial for an effective management (Beck et al. 2001). The persistence of these gaps in understanding make trade-offs impossible to assess. This means that many concepts and models that are in common use nationally are unsupported by hard scientific understanding. Without detailed habitat-level information about ecological values, environmental offset schemes are likely to legitimise habitat destruction while simultaneously failing to properly compensate for the loss of ecological value (Cowell 1997, Gibbons and Lindenmayer 2007, New 2008).

Most studies that assessed habitat value of tropical estuaries focussed on mangroves, but this may not be appropriate for northern Australian fisheries due to their unique tidal and seascape contexts. Firstly, much of the work defining the value of mangroves to fish has been conducted in the micro-tidal Caribbean (e.g. Nagelkerken et al. 2001, Mumby et al. 2004), with less evidence from meso- and macro-tidal areas such as much of the Indo-Pacific (Dorenbosch et al. 2005). Because of the paucity of information, evaluations from the Indo-Pacific are often heavily dependent on literature conclusions drawn from the Caribbean (e.g. Goudkamp and Chin 2006). Furthermore, all species that use mangroves in meso- and macro-tidal northern Australia, must also use sub-tidal habitats. Mangrove areas are only available to nekton when inundated (Minello et al. 2012, Baker et al. 2015), so fish must spend a large proportion of their time in sub-tidal habitats of estuaries and near-shore areas (Laegdsgaard and Johnson 1995, Sheaves 2005, 2009). Thus, the habitats used at these times must be as important for nursery functioning as the better studied intertidal mangrove habitats (Johnston and Sheaves 2007). Indeed, a study targeting utilisation of mangroves, that was conducted as part of this project (Sheaves et al. 2016), suggests they are not as extensively used by fisheries species as previously thought.

While extensive research has been carried out in estuaries, large areas of the subtidal, including significant habitat types, have not been adequately assessed as fish habitats even in the most basic sense. These deep estuary areas present a range of challenges to detailed study, and these difficulties have limited ecological research. For example, high turbidity, the presence of the estuarine crocodile *Crocodylus porosus* and a lack of adequate remote sampling technology kept estuarine benthic areas deeper than 2m (i.e. the depth accessed by most netting methods) relatively unexplored, in terms of both benthic habitats and the animals that use them (Sheaves 1992). In Australia, the few studies that sampled these areas used highly selective gears either over a restricted set of smooth bottom habitats (Blaber et al. 1989) or, by using baited fish traps, sampled a subset of the assemblage attracted to baited traps (Sheaves 1998). As many of these challenges are faced by estuarine ecologists globally, the situation is mirrored globally, with most research in deeper areas restricted to smooth bottom habitats (e.g. Minello et al. 2008). Consequently, there have been no notable advances in knowledge of deep water estuary habitats in the past decade (as reviewed in Blaber 2013).

Studies that tried to quantify or estimate the fisheries value of coastal habitats have previously been unable to use equivalent sampling techniques across multiple habitats. Deeper open bottom habitats have been sampled by beam trawling (e.g. Marshall and Elliott 1998), but these methods are unviable in complex habitats. In shallow and intertidal waters, cast netting and other techniques such as block and fyke netting have been used (Barko et al. 2004, Johnston and Sheaves 2007). Very little sampling has been conducted directly in structured subtidal habitats such as woody debris, with the exception of a few studies using fish traps (Sheaves 1992, 1996). All of these techniques have their own sampling biases and tend to target different components of the fish assemblage (Butcher et al. 2005, Steele et al. 2006), and are therefore difficult to integrate into an overall fish-habitat utilisation understanding. However, recent advances in cost and accessibility of underwater video technology allow us to remotely survey areas in a much less selective way (Cappo et al. 2003a), and opened new methodological pathways for understanding the distribution patterns of coastal fish fauna. By using underwater video, we can now use the same gear in any habitat, making results directly comparable and allowing the relative utilisation of different habitats by the different size classes of the various fisheries species to be assessed.

Another aspect that hindered the objective classification and assessment of habitat value was the use of *a priori* groups. Operating without habitat level information makes it hard to even begin carving up coastal systems into legitimate ‘habitat types’ without introducing subjective bias imported either from understanding of other ecological systems or due to pragmatic decisions made for convenience. Machine learning techniques now allow the distribution of individual species and cohesive communities to reveal ecologically meaningful habitat attributes without constraining outcomes by the use of *a priori* categories, and in many ways they provide the most accurate method for determining fish habitat relationships (Knudby et al. 2010). Here, we combine new advances in sampling technology and newly available statistical tools to develop detailed models of the life history stage-specific habitat utilisation of key coastal and estuarine fisheries species, and provide the latest ‘best practice assessment’ of the fisheries value of the coastal habitats of north-eastern Australia.

2. Methods

2.1. Fish surveys

2.1.1. Survey location

Sampling was conducted in the Hinchinbrook region (18˚20′ S, 146˚10′ E), in the wet tropics of north-eastern Australia (Figure A2-1), between November 2012 and December 2015. Sampling occurred in all months outside the North Australian Monsoon (typically January – April) when water clarity was too poor for successful video sampling. The Hinchinbrook region is ideal for addressing the objectives of this project as it contains almost the entire breadth of benthic habitats available to fisheries species in a single area. This allowed the diversity of habitat variation to be encompassed without confounding among-habitat differences with differences among regions. We aimed to survey all habitats available to coastal fisheries species. Surveys were carried out in a range of coastal environments including the downstream reaches of freshwater creeks and rivers, tidal creeks, the Hinchinbrook estuary, inlets and bays, beaches and headlands. Areas of depth between 0.5m and 20m were sampled. The Hinchinbrook estuary alone covers a total area of 192km^2 (Alongi et al. 1998). The majority of that area is sub-tidal (110km^2, 57%) while the remaining area consists of intertidal mangrove forest (70km^2) and intertidal sand and mud flats (12km^2).

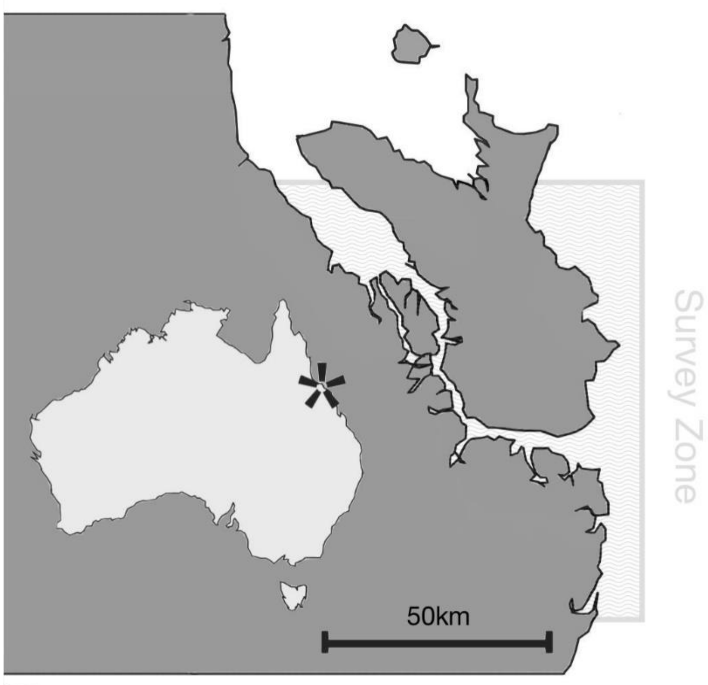

Figure A2-1. Location of the Hinchinbrook region in NE Australia, and the boundaries of the survey zone within which all rapid video point census surveys were carried out.

2.1.2. Rationale

Visual point census techniques have been used successfully to examine fish habitat relationships in other environments (St John et al. 1990), and fixed underwater video units can be used for this purpose in a variety of situations. A point census provides an assessment of fish assemblage characteristics at a fixed location and can be used to pair fish assemblage information with the characteristics of that location. By combining information from many points over an area, it is possible to generate detailed data on the distribution of fish species and equate changes in assemblage characteristics with changes in habitat variables (Yoklavich et al. 2000, Hannah and Blume 2012). With the development of compact, affordable underwater video technology, visual point census can be carried out remotely with high replication. In deeper waters this provides a non-destructive technique for use in areas that would otherwise require trawl sampling, and can also be used in structured habitats that cannot be trawled (Williams et al. 2010). While a remotely operated vehicle (ROV) could have been used in these areas to conduct fish surveys via video transect, the impact of the unit on fish behaviour can be significant (Stoner et al. 2008), and indeed pilot studies using a ROV indicate that many fish flee before they are within range to be identified. Similar behavioural impacts have been noted for diver conducted visual surveys (Thompson and Mapstone 1997). In contrast, unbaited fixed underwater video drop camera units that consist of a small motionless unit produce minimal disturbance, with fish continuing their normal behavioural patterns when cameras are deployed (Table A2-1). Additionally, point based underwater video census are more powerful in detecting spatial changes in assemblage metrics than video transects (Langlois et al. 2010). In addition, the deployment of many video units allows for detailed coverage of large areas and the implementation of high replication making this technique ideal for studies of broad-scale fish distribution and habitat relationships (Hannah and Blume 2012).

2.1.3 Development

The method used in this study has been developed over several years by the Estuary and Coastal Ecosystems Research Group as best practice for modelling fish-habitat relationships. It involves rapid fish assemblage assessments using underwater video point censuses. A series of trials were conducted to assess the effectiveness of the technique and refine the design and methodology to suit the requirements of the current study (Table A2-1).

2.1.4 Video camera deployment

The video units are deployed from a vessel, allowing sampling a range of otherwise restrictive locations due to the presence of large predators, most notably estuarine crocodiles (Read et al. 2005) that are dangerous to humans (Caldicott et al. 2005). In each survey, location efforts were made to sample the entire breadth of habitat variation present. Deployments were large enough (>30 samples per site per day, with multiple days for each site = ~100 deployments per location) that while not strictly stratified, habitat variability could be accounted for with the analytical pathway detailed below. All available depth/substrate combinations were sampled. However, not all combinations of depth and biotic habitat were possible because nearly all biotic features (e.g. seagrass) are restricted to particular depth zones. Consequently, the samples collected in this study could not be completely orthogonal, yet they encompass the major variation in substrate across all depths in all sites as comprehensively as possible (Annex A2-Tables 1 and 2).

Table A2-1. Issues, trials and solutions in adapting the use of video point census to the estuarine environment.

Issue	Trial	Solution
Low light levels	Camera units were deployed in deep water (>10m) during suboptimal low light conditions. The video data from these tests provided satisfactory visible distance (>1m) and detail discrimination.	To improve video data further, alterations were made to camera settings to increase the use of available light for deeper deployments. During analysis, image enhancement was carried out when necessary to improve contrast levels.
Camera unit stability	Camera units were deployed in a variety of substrates to determine their performance. Deployments on flat, open substrates were found to be largely successful when disturbed sediment had cleared (1-2 minutes). Deployments on rocky substrate resulted in only 1/3 useable samples. In unusable samples, the field of view was either blocked by rock or was facing upwards, obscuring surrounding habitat characteristics and the demersal fish taxa present.	A broader, heavier base was retrofitted to the units. This design improved the stability of the unit on uneven bottom, limited toppling in any direction and allowed the unit to sit above crevices in which vision would be obscured. As a result, a far greater fraction (9/10) useable video samples were retrieved from rocky areas.
Low visibility	Camera units were deployed in range of visibility conditions and at different points during the tidal cycle.	To ensure consistent high visibility, sampling was carried out during neap tides. A visibility indicator was fixed within the camera's field of view and used as a standard measure of visible distance (0.5m). Samples with visibility <0.5m were discarded.
Behavioural impacts	A set of camera units were deployed, and a subsequent set were deployed within their field of view. Fish response to the introduction of the second set was noted. Fish already present in the area were occasionally attracted to the camera for the first ~ 2 minutes, no new individuals or flee responses were observed.	No change required.

Each video recorded for 15 minutes and provided a point census of fish taxa present as well as biological and structural habitat characteristics, a technique ideal for understanding broad-scale fish distribution and habitat relationships (Hannah and Blume 2012). Pressure gauges were attached to each camera unit to record depth. Cameras were always spaced >20m apart to ensure independence and their positions were recorded using GPS. The >20m spacing was considered a minimum with cameras actually spaced at much greater distances in almost every case. Presence (e.g. Harvey et al. 2007), was recorded as well as an abundance estimate commonly used in video surveys, MaxN (Cappo et al. 2003b). When reliable, Max N can be used to develop models of habitat relationships. However, in the present study it was considered prudent to use simple presence data as well. Reliable presence/absence data can provide a proxy for abundance, because fish that are abundant tend to also occur more frequently than less abundant fish (Royle and Nichols 2003, Sheaves and Johnston 2009), and presence data is known to produce more reliable models of species-habitat relationships (Elith et al. 2006). Presence data are also more robust in the face of differences in water clarity because biases are minimised by excluding the numeric component of count data. In the current study potential biases were further reduced by only including videos where water clarity was above a minimum threshold. A 0.5 m long leg with a vertical plastic strip, to provide a visibility measure, was fixed in the centre of the camera’s field of view to provide a standard measure of distance and water clarity. Even under the best visibility conditions fish could rarely be reliably identified beyond ~2m. Hence, the effective sampling range is between 0.5-2m.

2.2. Video analysis

For video analyses, fish were identified to the lowest taxonomic level possible. Some taxa could only be identified to genus or family level, as the features that distinguish some closely related species (e.g. fin ray counts) were not visible on camera or could not be distinguished due to a lack of water clarity or colour definition. Accordingly, for detailed analysis taxa were grouped to genus or family level when none or only a small proportion of individuals could be identified to species level. When a sufficiently large data set for a species was available, and when possible, different life stages of a species were treated as separate entities in analyses. When juveniles could be differentiated, classification as juveniles was based on juvenile markings and patterns of shading, rather than size. Identifications were reviewed by at least two additional experts to ensure consistent identification.

Habitat attributes from each video sample were categorised based on the range of characteristics visible in the field of view following Ball et al. (2006), with a reduced number of modifiers for simplicity (Table A2-2). Two attributes were used: substrate texture and dominant biota. Each video sample was assigned one category for each attribute. When attributes were mixed, we assigned the sample to the largest substrate size and most dominant biota present.

2.3. Statistical Analyses

Rather than imposing predetermined ‘habitats’ onto the data and analysing for differences in fish species composition between them, Classification and Regression Tree (CART) analyses were, an approach that does not require *a priori* grouping. This approach allows differences in fish presence and species composition to drive the identification of the habitat characteristics that are important to fish, and can be used to defined the typological boundaries of these habitat units empirically.

First, the attributes that drive the presence of any fish were determined. Samples were categorised according to whether any fish were present or not, producing a binary variable. Univariate classification tree analysis was then carried out on this binary variable for the entire data set using the ‘*party’* package in R (Hothorn et al. 2010), with the following predictor variables: dominant biota, substrate texture, location, depth, and tidal movement. Secondly, the variables that drove differences in species composition were determined using multivariate analysis. Based on the univariate tree described above, combinations of variable categories in which few fish occurred were excluded. All video samples where no fish were present, and taxa that occurred rarely (those with <10 total presences) were also excluded from this analysis. Using species level abundance information (maxN), the remaining data was submitted to multivariate regression tree analyses using the ‘*mvpart’* package in R (De’ath 2007, Ouellette and Legendre 2012). The regression tree was constructed from a Bray-Curtis similarity matrix of maxN, and tree size was based on lowest cross-validation error. To test the robustness of this output, several trees were constructed, based on different measures of distance of maxN including binary (Jaccard) and numerical (Bray-Curtis), using different tree selection criteria, and analysing by either species or genus. All trees contained the same basic structure present in the Bray-Curtis base tree, which is presented in the results.

Table A2-2. Definition of habitat attributes used throughout this report

Variable	**Category**	**Definition**
Substrate texture	solid	consolidated/unbroken rock pavement
	large boulder	grainsize >630mm
	boulder	grainsize 200-630mm
	cobble	grainsize 63-200mm
	gravel	grainsize 2-63mm
	shells	grainsize 2-63mm, composed of shells
	fine sediment	silt and sand, grainsize 0.002-2mm
Dominant biota	bare	no visually obvious biota
	bioturbated	substrate physically altered by biotic activity – e.g. burrows and castings
	algae	Visually obvious filamentous algae
	seagrass	members of the following seagrasses genera: *Cymodocea, Halophila, Halodule, Thalassia and Zostera*
	macro algae	members of the phyla Ochrophyta and Chlorophyta
	ESI	Encrusting Sessile Invertebrates, including: cnidarian structures, encrusting hard coral, barnacles, soft coral, sponges of the family Tetillidae as well as other unidentified sponges
	SFSI	Structure Forming Sessile Invertebrates, including: branching cnidarian structures, encrusting hard coral, barnacles, soft coral, sponges of the family Tetillidae as well as other unidentified sponges
	FWD	Fine Woody Debris: Fine branching woody debris only
	LCWD	Low Complexity Woody Debris: medium to large woody debris with simple form (little to no interstitial spaces) – e.g. logs without branches
	HCWD	High Complexity Woody Debris: medium to large woody debris with complex form but no fine structure (large interstitial spaces only) e.g. trees with main branches
	FHCWD	Fine High Complexity Woody Debris: medium to large woody debris with complex form AND fine structure (large and small interstitial spaces) e.g. trees with main branches and small branches or a large collection of fine-large branches

Based on the combinations of predictor variables that were most important in driving both fish presence and assemblage composition, the set of ecologically meaningful habitat categories appropriate for coastal fishes were then determined. Using this new classification scheme, we developed a model of the probability of encountering a fish in each of these new habitats based on all data using stepwise logistic regression. Finally, the individual probabilities of encounter for each of the 21 common taxa in each of these habitats were calculated.

3. Results

A total of 113 different taxa from 40 families were identified. The level of taxonomic resolution varied, resulting in 93 species, 18 genera and 2 families. Of these taxa, 87 are globally important to fisheries, and 51 are of importance to fisheries in the region (Table A2-3).

The broad data set produced encompasses multiple seasons over multiple years for most habitat and Process Zone combinations (Annex 2, Tables 1 and 2). The resulting data set has a large amount of species specific and location specific detail, as well as a large amount of variability associated with its spatial and temporal breadth. This data set was examined for patterns and structures that remain robust to this variability to ensure interpretations were valid and applicable outside the study system and time window.

3.1. Defining ecologically meaningful habitats

3.1.1 Analysis of overall fish absence and presence

Overall, habitat attributes were the main drivers determining the occurrence of fish in a video sample. Random Forest analysis revealed that 'Substrate texture' and 'Dominant biota' were the two most important variables in predicting the presence or absence of fish (Fig. A2-2). Two other habitat related variables then followed - 'Depth' and 'Process zone'. This is an important result in its own right, indicating for instance that given a specific set of habitat qualities, the pattern of presence of fish remains reliably constant throughout the year. Additionally, in order to avoid over-fitting when constructing Classification and Regression Trees, it is appropriate to avoid variables that do not explain much variation (De'ath and Fabricius 2000). Accordingly, we only used these four important habitat variables identified in Random Forest analysis to construct our univariate tree.

Table A2-3. Fish taxa identified in video surveys in the Hinchinbrook region, north Queensland, Australia. ∆ = species recorded in both early juvenile and late juvenile forms. * = juveniles present. Ω = species considered important for commercial or recreational fisheries by Queensland fisheries authority. † = species considered important for commercial or recreational by international (FAO) fisheries authorities. aq = recognized as important for the aquarium trade by international (FAO) fisheries authorities.

Family	**Taxon**	
Acanthuridae	Ω†	*Acanthurus auranticavus**
Ambassidae		*Ambassis* spp.
		Ambassis vachelli
Apogonidae	aq	*Apogon hyalosoma*
	aq	*Apogon* spp.
Ariidae	Ω	*Neoarius graeffei*
Carragidae	Ω†	*Caranx ignobolis*
	Ω†	*Caranx lugubris*
	Ω†	*Caranx papuensis*
	Ω†	*Caranx sexfasciatus*
	Ω†	*Scomberoides commersonnianus*
	Ω†	*Scomberoides lysan*
	Ω†	*Scomberoides tol*
	Ω†	*Trachinotus* spp.
Chaetodontidae	aq	*Chelmon muelleri*
	aq	*Parachaetodon ocellatus*
Clupeidae	Ω	Clupeidae spp.
	Ω	*Herklotsichthys castelnaui*
	Ω	*Herklotsichthys* spp.
	Ω	*Spratelloides* spp.
Dasyatididae	Ω	Dasyatididae spp.
Drepaneidae	Ω	*Drepane punctata*
Engraulidae	Ω	Engraulidae spp.
	Ω	*Stolephorus indicus*
Ephippidae	Ω	*Platax pinnatus*
Gerreidae		*Gerres filamentosus**
	Ω	*Gerres oyena**
	Ω	*Gerres subfasciatus*
Gobiidae		*Acentrogobius* spp.
		Istigobius spp.

Family	Taxon	
Gobiidae (cont.)		*Redigobius balteatus*
Haemulidae	Ω†	*Pomadasys argenteus**
	Ω†	*Pomadasys kaakan**
	Ω†	*Pomadasys maculatus**
	Ω†	*Plectorhinchus gibbosus**
	Ω†	*Diagramma pictum**
Kuhliidae	Ω	*Kuhlia rupestris*
Kyphosidae	Ω	*Kyphosus vaigiensis*
Labridae		*Halichoeres nigrescens*
		Halichoeres kneri
		Choerodon spp.
Latidae	Ω†	*Psammoperca waigiensis*
	Ω†	*Lates calcarifer**
Leiognathidae	Ω	*Nuchequula gerreoides** Δ
		Gazza spp.
	Ω	*Leiognathus equulus*
	Ω	*Leiognathus decorus*
	Ω	*Secutor ruconius*
Lethrinidae	Ω†	*Lethrinus lentjan**
	Ω†	*Lethrinus genivittatus**
Lutjanidae	Ω†	*Lutjanus argentimaculatus** Δ
	Ω†	*Lutjanus fulviflamma** Δ
	Ω†	*Lutjanus fulvus**
	Ω†	*Lutjanus johnii**
	Ω†	*Lutjanus lemniscatus**
	Ω†	*Lutjanus rivulatus**
	Ω†	*Lutjanus russellii** Δ
Megalopidae	Ω†	*Megalops cyprinoides*
Monacanthidae		Monacanthidae spp.
Monodactylidae	Ω	*Monodactylus argenteus*
Mugilidae	Ω†	*Liza subviridus*
	Ω†	*Liza vaigiensis*
	Ω†	*Mugil cephalus*
	Ω†	*Valamugil buchanani*
Mullidae		Mullidae spp.
Nemipteridae	Ω	*Pentapodus* spp.*
	Ω	*Scolopsis* spp.*
Platycephalidae	Ω†	*Platycephalus fuscus*
	Ω†	*Platycephalus* spp.

Family	Taxon	
Pomacentridae	Ωaq	*Chrysiptera unimaculata*
	aq	*Chrysiptera unimaculata*
	aq	*Neoglyphidodon melas*
	aq	*Neopomacentrus azysron*
		Neopomacentrus bankieri
	Ω	*Neopomacentrus teniuris*
	Ω	*Abudefduf bengalensis*
	Ωaq	*Pomacentrus* spp.
Pseudomugilidae		*Pseudomugil signifier*
Scaridae	Ω†	*Scarus* spp.*
Scatophagidae	Ω	*Scatophagus argus*
	Ω	*selenotoca multifasciata*
Scombridae	Ω†	*Scomberomorus* spp.
Serranidae	Ω†	*Epinephelus coioidies**
	Ω†	*Epinephelus malabaricus**
	Ω†	*Epinephelus coeruleopunctatus**
Siganidae	Ωaq	*Siganus fuscescens*
	Ωaq	*Siganus javus** ∆
	Ωaq	*Siganus lineatus**
	Ωaq	*Siganus spinus*
	Ωaq	*Siganus virgatus*
Sillaginidae	Ω†	*Sillago analis*
	Ω†	*Sillago ciliata*
	Ω†	*Sillago sihama*
Sparidae	Ω†	*Acanthopagrus pacificus** ∆
	Ω†	*Acanthropagrus australis** ∆
Sphyraenidae	Ω†	*Sphyraena barracuda*
	Ω†	*Sphyraena obtusata*
Terapontidae	Ω†	*Helotes sexlineatus**
	Ω†	*Mesopristes argenteus*
	Ω†	*Pelates quadrilineatus**
	Ω†	*Terapon jarbua**
	Ω†	*Terapon puta**
	Ω†	*Terapon theraps**
Tetraodontidae	Ωaq	*Arothron hispidus*
		Arothron manilensis
		Arothron reticularis
		Arothron stellatus
	Ω	*Chelonodon patoca*

Family	Taxon	
	aq	*Lagocephalus sceleratus*
	Ω	*Tricanthus nieuhofi*
Toxotidae	Ωaq	*Toxotes chatareus*

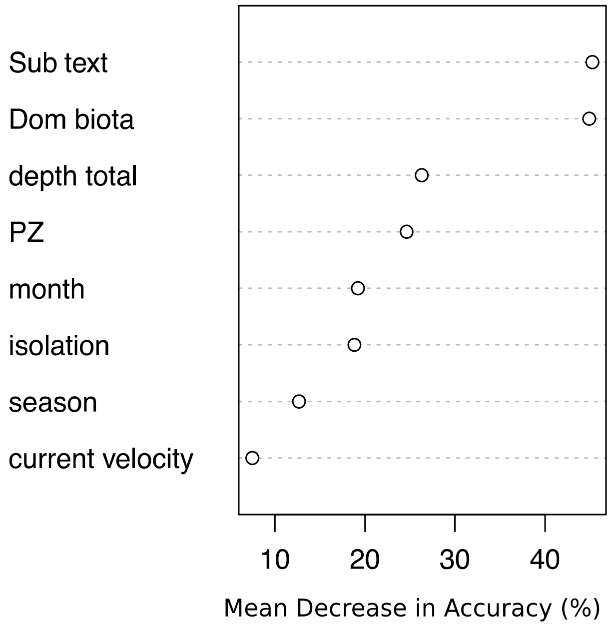

Figure A2-2. Variable importance plot produced using Random Forest. Mean decrease in accuracy details the contribution each variable makes towards the accuracy of classification and regression tree modelling of fish presence.

As expected, the univariate classification tree built using the entire data set found both ‘Substrate texture’ and ‘Dominant biota’ to be the most useful in sorting samples according to fish presence (Fig. A2-3). In some areas, fish were rarely encountered. In particular, only 30% of samples contained fish when in embayments in areas with fine substrates (gravel, shell grit, sand or mud) and either no discernible biota or fine debris. In rocky areas (areas with substrate textures of cobble, boulder or large boulder) and treed areas (whether live mangrove forest or larger woody debris) fish were frequently encountered. Within particular combinations of substrate texture and dominant biota, process zones and depth were important in explaining fish presence. This points to the primacy of physical habitat attributes and the secondary effect of the location and depth in determining a habitat’s utilisation by fish.

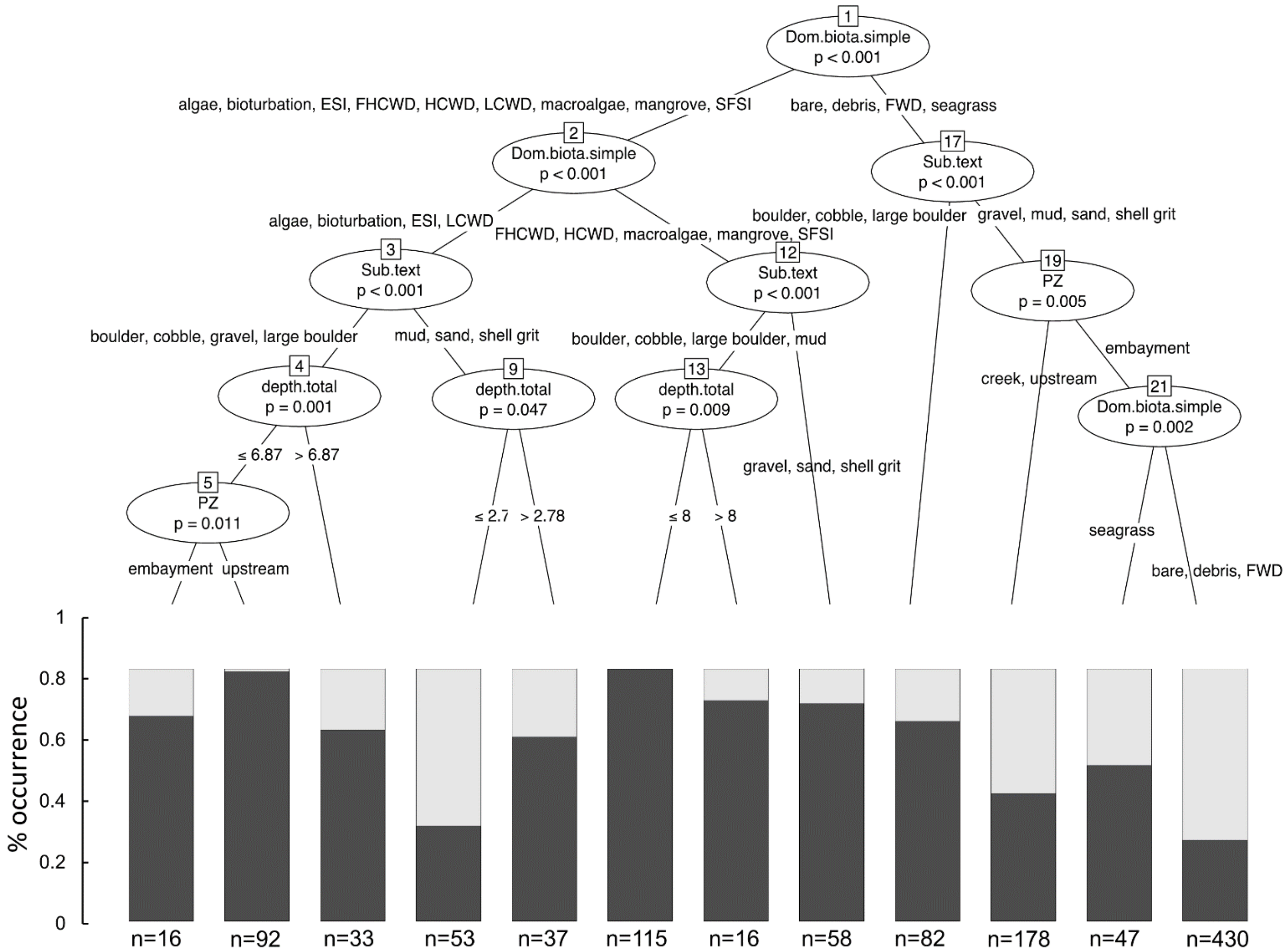

Figure A2-3. Univariate classification tree based on the presence or absence of fish, performed on all samples (n=1158). Each of the splits are labelled with the variable that determined the split and the categories separated by the split. Black bars below terminal nodes indicate the percentage of samples where fish were present for each respective terminal node.

There were other interesting distinctions between habitat attributes. For example, equivalently structurally complex types of dominant biota grouped together, despite qualitative differences. Rather than the class of dominant biota types that we would call woody debris grouping together, FWD paired with seagrass, LCWD paired with ESI, bioturbation and algae, and the high complexity woody debris paired with mangroves, SFSI and macroalgae. This grouping based on structural complexity reveals a fundamental driver of fish presence in this system: large complex structure.

3.1.2 Analysis of fish community composition

In order to examine species-specific patterns of utilisation, habitat attributes identified in the previous analysis as having low occurrences of fish (i.e. when <50% of samples contained fish) were excluded from the following multivariate analysis because they contributed many zeros to the data matrix without providing substantive information. This included samples from embayments with finer sediment textures that were either bare or contained fine debris, as well as shallow (≤2.8m) fine sediment textures that either featured algae, substantial bioturbation, low complexity sessile invertebrates or low complexity woody debris.

Performed on the remaining 567 samples, multivariate classification tree analysis of assemblage composition was able to distinguish four major habitat types (Fig. A2-4): rocks from creeks and upstream (referred to as ‘creek rock’), rock from embayments (referred to as ‘embayment rock’), treed habitat (both mangrove forest and woody debris) and open, low complexity habitat (which included seagrass). The arrangement of the tree has several ecologically important features: 1) Rocky areas in different process zones were as different as *all* treed habitats were from *all* low complexity habitats, 2) Mangroves and woody debris have essentially the same assemblage composition, 3) The final regression tree model is relatively simple, requiring few attributes to describe the pattern of habitat utilisation. The various other attributes found to be important in determining fish presence (in Fig. A2-3) do not affect assemblage composition, but simply affect the chance of encountering any fish within one of these four major assemblage groups.

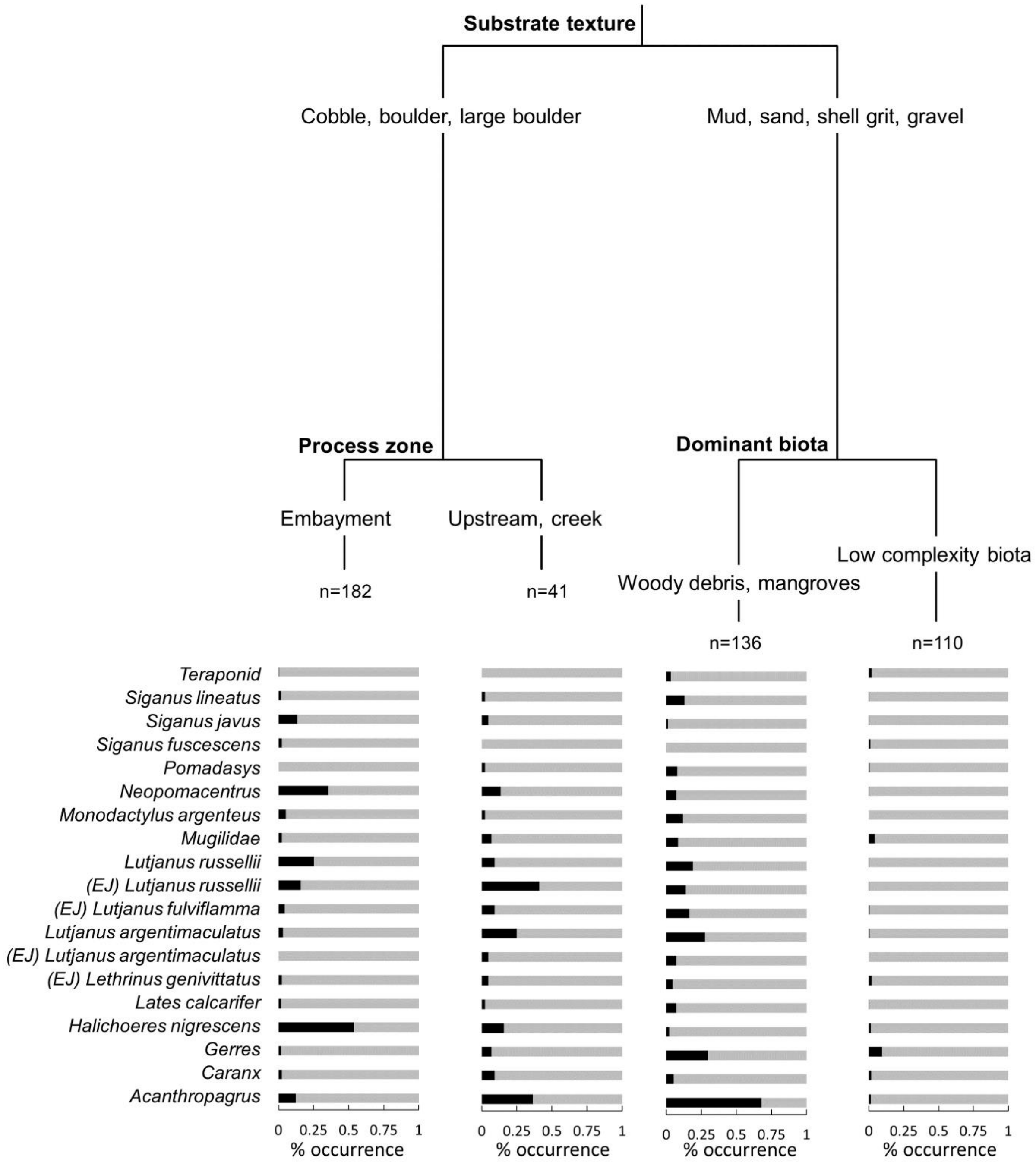

Fig. A2-4. Multivariate regression tree showing the major divisions in the data based on assemblage composition. Each of the splits are labelled with the categories separated by the split. The length of descending branches is proportional to divergence between groups. Bar graphs below terminal nodes show the proportion of each common taxa in the samples sharing the attributes identified for each terminal node.

3.2. Defining fauna-habitat relationships

Six major habitat types were distinguished: creek rock, embayment rock, mangroves, woody debris, open bottom and seagrass (Fig. A2-5). These were based on the habitats distinguished by multivariate analysis, and on other additional factors. In multivariate analysis, seagrass habitat was grouped with open bottom habitat, and woody debris habitat grouped with mangrove habitat. To test this grouping of habitats that are usually treated as distinct in coastal zone science and management, these four putative habitat types were treated as distinct in the following analyses. Overall, fish presence in these six habitat types was investigated using stepwise logistic regression (Fig. A2-6). Creek rock, embayment rock, mangroves, woody debris, open bottom habitat types were good predictors of fish presence, and all had relatively low error margins. Seagrass proved to be the exception, with a large margin of error associated with fish presence in this habitat type.

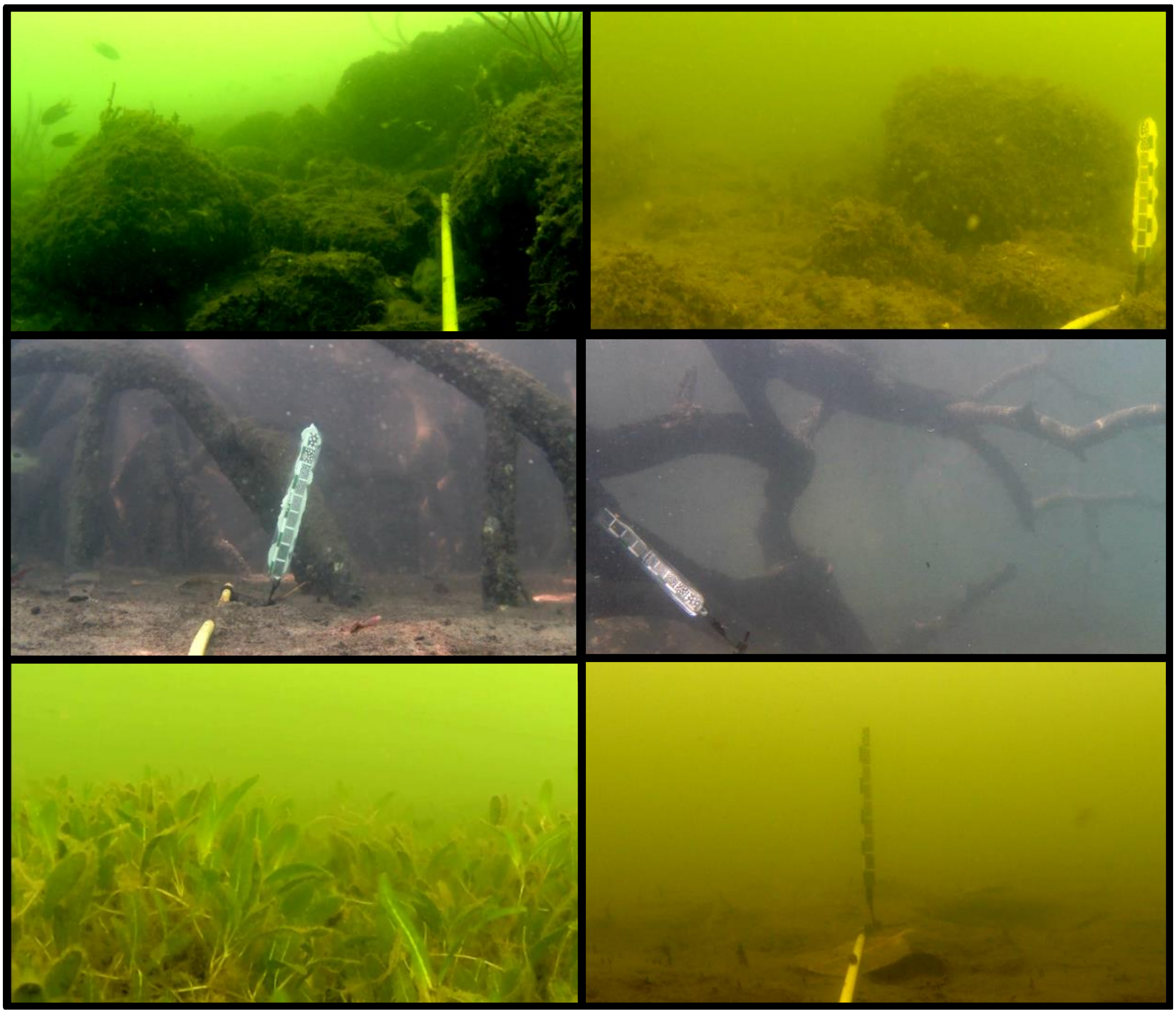

Figure A2-5. The six major habitat types of interest distinguished in this study, left to right: creek rock, embayment rock, mangroves, woody debris, seagrass and open bottom.

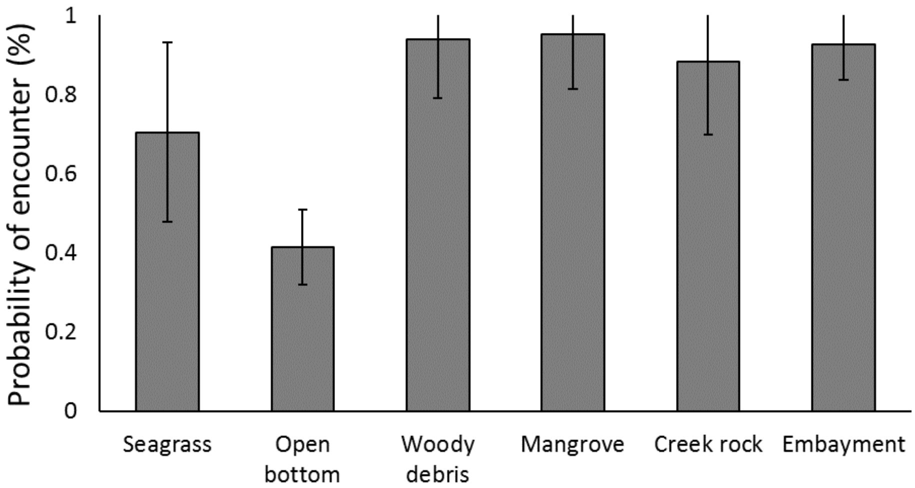

Figure A2-6. Probability of encountering any fish in the six distinct habitat units identified based on stepwise logistic six-habitat model of binary fish presence/absence.

Using species specific data, probability of encounter was calculated for the 21 commonly encountered taxa or life-stage groups (present in > 2.5% of all samples), according to the six habitat categories determined above (Table A2-2). Below we discuss these relative occurrence patterns, as they reveal some important details both at a species level and habitat level.

3.2.1 General patterns

Overall, no particular habitat was responsible for the majority of occurrences of all species, and no common species or group was entirely restricted to a single habitat type. However, most species or groups were predominantly found in a single habitat type. There were very few true generalists (Mugilidae, *Caranx* spp., *Gerres* spp.) present among the commonly encountered species and groups. Below we investigate the grouping of seagrass habitat with open bottom habitat, and woody debris habitat with mangrove habitat that was identified in the multivariate analysis.

Open bottom habitat was not particularly important to any commonly encountered fish taxa. Only one group of commonly encountered fish had a substantial presence (>10% of proportional occurrences) in this habitat: the Mugilidae (the mullets); and this group was evenly spread between four habitat types. No common fish group is entirely, or even particularly (i.e. >40%) concentrated in open bottom habitat, while three common species were particularly (>40%) concentrated in the seagrass habitat, and four had a substantial (>10%) presence there. The similarity between these two habitats found in multivariate analysis was likely due to the presence of a number of generalist groups found across all habitats (*Caranx* spp., *Gerres* spp. and Mugilidae) and the absence of structure-associated species. However, while the overall fish assemblage may be similar between seagrass and open bottom habitats, their value for particular common species is likely to be very different.

All species or groups that were commonly found in mangrove habitat were also found in woody debris habitat, except for Teraponids. This mirrors the result from multivariate analysis that mangrove and woody debris habitats share a very similar assemblage composition. Woody debris contains more common taxa than mangroves however, supporting a substantial presence (>10% of encounters) of all but three common species or groups.

3.2.2 Habitat complexes

Various combinations of structured habitat appear to support most common species, and woody debris unite the majority of these combinations (Fig. A2 2-7). In particular, five taxa groups use mangroves, creek rock and woody debris. This represents approximately equal utilisation of intertidal and subtidal structured habitat. Two taxa, *Neopomacentrus* spp. and *Siganus javus*, use creek rock, embayment rock and woody debris extensively, representing the use of subtidal structured habitat across process zones. Two other taxa, *Lutjanus russellii* (both early juveniles and juveniles) and *Lates calcarifer* used all four of the structured habitat types, which represents habitat use across the intertidal-subtidal realms as well as across process zones. Several individual species or groups link pairs or trios of habitats, including seagrass beds, in unique ways.

When sufficient data was available, it was possible to treat the different life stages of a species as separate entities. Within the *Lutjanus* and *Acanthopagrus* genera, we found clear distinctions between early juvenile and late juvenile habitat use patterns (Table A2-4). In general, early juveniles were particularly concentrated in a single habitat type, and late juveniles were more evenly spread between three or four habitat types. In addition, there was clear partitioning between early juveniles of different *Lutjanus*, *Lethrinus* and *Acanthopagrus* species, as early juveniles tended to predominantly use a specific habitat that differed among species. For example, *Lutjanus argentimaculatus* used mostly woody debris while *Lethrinus genivittatus* used seagrass beds, *Lutjanus russellii* creek rock*, and Acanthopagrus* spp. mangroves. This information is summarised in Table A2-6, where this is compared to previous knowledge (see discussion section for detail).

Table A2-4. Probability of encounter for the 22 commonly encountered taxa or life stage groups in the coastal habitats of the Hinchinbrook region, according to the six habitat categories determined by previous analyses, performed on all samples. Colours show the relative concentration of occurrences for each species or group across the different habitats. Yellow indicates that between 10-40% of the occurrences of that species were in the particular habitat, red indicates that >40% of occurrences of that species were in that habitat. (EJ) denotes the early juvenile form of a species – where this is denoted, the taxa name without (EJ) refers to the late juvenile/adult form.

Species	**seagrass**	**OB**	**WD**	**mangrove**	**Creek rock**	**Embaymt/ rock**
Acanthopagrus	0.00	0.01	0.45	0.63	0.37	0.12
(EJ) Acanthopagrus	0.00	0.00	0.09	0.31	0.04	0.01
Caranx	0.05	0.01	0.05	0.04	0.10	0.02
Gerres	0.13	0.09	0.15	0.37	0.06	0.02
Halichoeres nigrescens	0.05	0.01	0.04	0.00	0.14	0.54
Lates calcarifer	0.02	0.00	0.08	0.06	0.02	0.02
Lutjanus	0.23	0.01	0.62	0.42	0.53	0.43
Lutjanus argentimaculatus	0.00	0.00	0.31	0.20	0.27	0.04
(EJ) Lutjanus argentimaculatus	0.00	0.00	0.13	0.01	0.04	0.00
(EJ) Lutjanus fulviflamma	0.00	0.01	0.15	0.14	0.10	0.04
(EJ) Lethrinus genivittatus	0.23	0.00	0.08	0.01	0.06	0.02
Lutjanus russellii	0.00	0.00	0.15	0.19	0.12	0.25
(EJ) Lutjanus russellii	0.00	0.00	0.17	0.09	0.43	0.15
Mugilidae	0.02	0.05	0.08	0.08	0.06	0.02
Monodactylus argenteus	0.00	0.00	0.13	0.09	0.02	0.05
Neopomacentrus	0.00	0.00	0.14	0.00	0.14	0.35
Pomadasys	0.00	0.00	0.08	0.07	0.02	0.00
Siganus fuscescens	0.10	0.00	0.00	0.00	0.00	0.02
Siganus javus	0.00	0.00	0.03	0.00	0.06	0.14
Siganus lineatus	0.03	0.00	0.09	0.14	0.04	0.02
Teraponidae	0.16	0.01	0.00	0.06	0.00	0.00

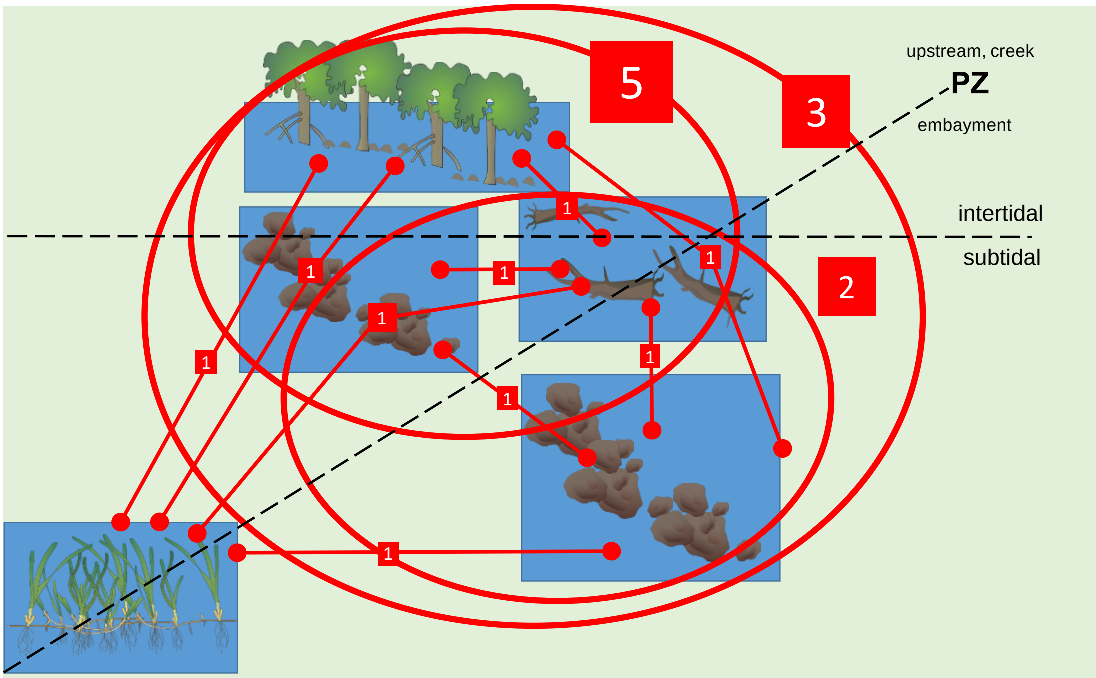

Figure A2-7. Visual depiction of habitat use patterns showing overlap in use of structured habitats. For details see Table A2-5 below.

Table A2-5. Details of multiple habitat use by common fish taxa.

Habitats	total taxa	taxa
Creek rock, Mangrove, Seagrass, Woody debris,	1:	*Caranx*
Creek rock, Mangrove, OB Woody debris,	1:	Mugilidae
Creek rock, Embayment rock, Mangrove, Woody debris	3:	(EJ) *Lutjanus russellii, Lutjanus russellii, Lates calcarifer*
Mangrove, Seagrass, Woody debris,	1:	*Gerres*
Creek rock, Seagrass, Woody debris,	1:	(EJ) *Lethrinus genivittatus*
Creek rock, Mangrove, Woody debris,	5:	*Siganus lineatus, Acanthopagrus, Pomadasys*, (EJ) *Lutjanus fulviflamma, Lutjanus argentimaculatus*
Embayment rock, Mangrove, Woody debris,	1:	*Monodactylus argenteus*
Creek rock, Embayment rock, Woody debris,	2:	*Neopomacentrus, Siganus javus*
Mangrove, Woody debris,	1:	(EJ) *Acanthopagrus*
Creek rock, Woody debris,	1:	(EJ) *Lutjanus argentimaculatus*
Mangrove, Seagrass,	1:	Teraponidae
Embayment rock, Seagrass,	1:	*Siganus fuscescens*
Creek rock, Embayment rock,	1:	*Halichoeres nigrescens*

3.3. Settlement hotspots

Settlement hotspots (Fig. A2-8) are areas where large numbers of fish larvae descend from the water column onto benthic habitat in order to metamorphose into the juvenile form. In our study, settlement hotspots were concentrated within the ‘creek’ Process Zone, with nine occurrences there, three in embayments and none upstream. They occurred mostly over open bottom habitats that were either bare or vegetated with filamentous algae or seagrass. As settlement hotspots are such transitory phenomena, they were difficult to sample and occur so intermittently within our survey data set that we were unable to perform statistical analysis on their occurrence. However, their existence points to the potential importance of simple habitats within creeks in relatively shallow water (1-4m), which is not highlighted in the habitat relationships of common juvenile and adult fauna.

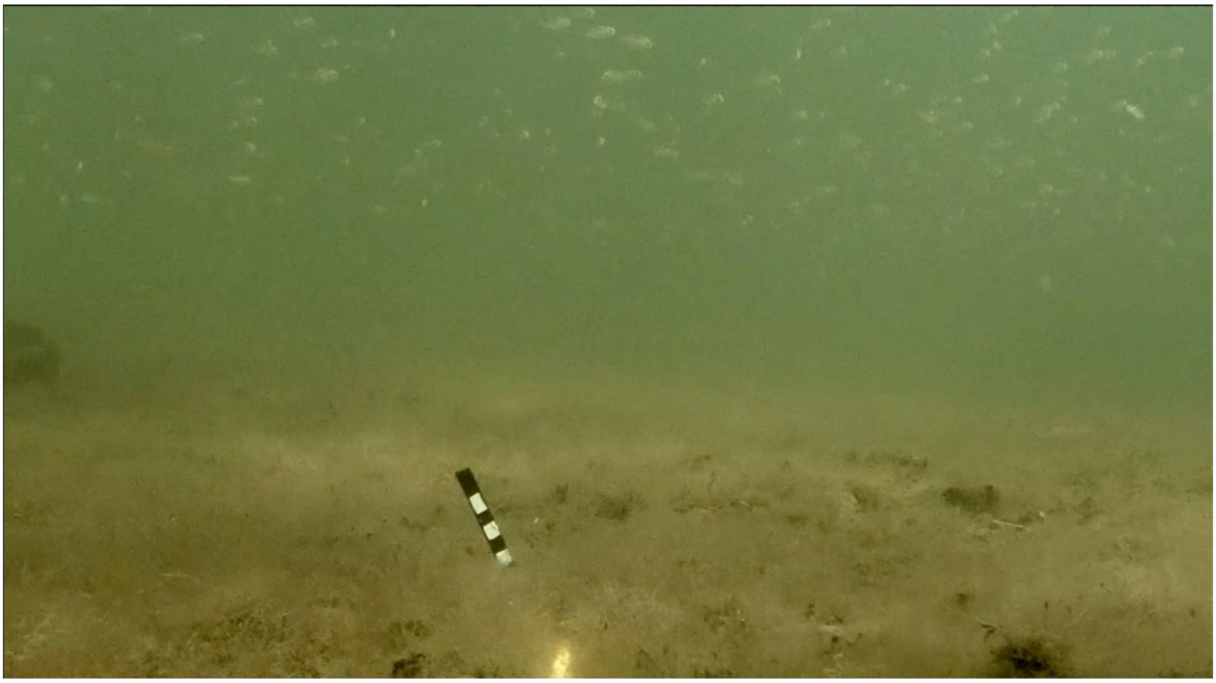

Figure A2-8. Still image from a video sample depicting a settlement hotspot. Small unidentifiable fish at larval-settlement transition stage are visible at the top of the image, algae/seagrass bed is visible at bottom.

4. Discussion

4.1. Efficacy of technique: corroboration and new findings

In this part of the project, we compare our occurrence data across habitats and process zones with findings from previous studies from the region (Table A2-6). In general, our video point census technique was able to corroborate and add to habitat and process zone use patterns previously recorded, with the major addition of two new habitat types – creek rock and embayment rock (Fig A2-9). Overall, this study added 140 new habitat specific occurrence records for 65 species, and for some species, habitat specific information was produced for the first time. For common species, a measure of the relative importance of individual habitat types was developed, allowing us to pinpoint which out of the range of habitats a species has previously been found in is the most important.

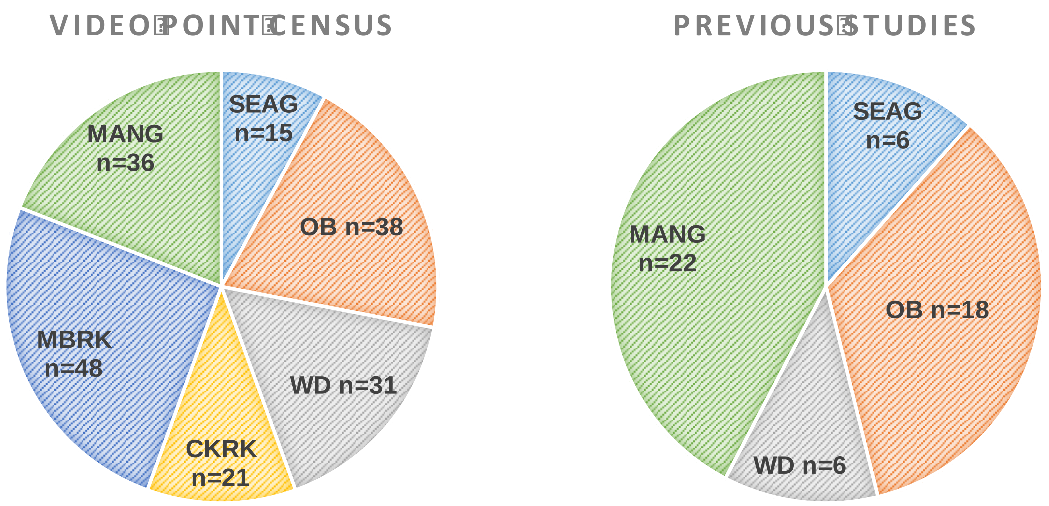

Figure A2-9. A comparison of recorded observations of common Australian finfish species in various coastal habitats generated from Table A2-6. In this figure, *n* refers to the number of species positively recorded in each habitat.

Table A2-6. The table below compares the habitat information on common Australian finfish species produced in this study (columns head rows in green) with information available in the international scientific literature (columns head rows in blue) (source: FRDC Project 2013/046: Milestone 2: Appendix 1: Annotated bibliography of habitat use by common Australian fisheries species, and Froese, R., and D. Pauly. FishBase. “www.fishbase.org”. Accessed April 2016.).

Family	Species	Seagrass	Open Bottom	Woody Debris	Creek Rock	Embayment Rock	Mangrove	PZ: Upstream	PZ: Creek	PZ: Embayment	Seagrass	Open Bottom	Woody Debris	Creek Rock	Embayment Rock	Mangrove	PZ: Upstream	PZ: Creek	PZ: Embayment
Acanthuridae	*Acanthurus auranticavus**	0	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0	0	1
Carragidae	*Caranx ignobolis*	1	1	0	1	0	1	0	1	1	0	0	0	0	0	1	0	1	0
	Caranx papuensis	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	0
	Caranx sexfasciatus	0	1	1	0	1	0	0	1	1	0	0	0	0	0	1	0	1	0
	Gnathanodon speciosus	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1
	Scomberoides commersonnianus	0	1	0	0	1	1	0	1	1	0	1	0	0	0	1	0	1	1
	Scomberoides lysan	0	1	1	0	1	1	0	1	1	0	0	0	0	0	0	0	1	1
	Scomberoides tol	0	1	1	0	1	1	0	1	1	0	0	0	0	0	0	0	0	1
Chaetodontidae	*Chelmon muelleri*	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	0
	Parachaetodon ocellatus	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	Herklotsichthys castelnaui	0	0	1	0	0	1	0	1	1	0	0	0	0	0	0	0	1	1
	Herklotsichthys spp.	0	0	1	1	0	1	0	1	1	0	0	0	0	0	0	0	1	1
Drepaneidae	*Drepane punctata*	1	1	1	0	1	1	0	1	1	0	0	0	0	0	0	0	1	1
Gerreidae	*Gerres filamentosus**	1	1	1	1	0	1	1	1	1	0	1	0	0	0	0	1	1	1
	*Gerres oyena**	1	1	1	0	1	1	0	1	1	0	1	0	0	0	0	0	1	1
Haemulidae	*Pomadasys argenteus**	0	0	1	0	0	1	1	1	0	0	0	0	0	0	1	0	1	1

Family	Species	Seagrass	Open Bottom	Woody Debris	Creek Rock	Embayment Rock	Mangrove	PZ: Upstream	PZ: Creek	PZ: Embayment	Seagrass	Open Bottom	Woody Debris	Creek Rock	Embayment Rock	Mangrove	PZ: Upstream	PZ: Creek	PZ: Embayment
	*Pomadasys kaakan**	0	1	1	1	0	1	1	1	0	0	0	0	0	0	0	0	1	1
	*Pomadasys maculatus**	0	1	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	1
	*Plectorhinchus gibbosus**	0	1	1	1	1	1	1	1	1	0	1	0	0	0	0	1	1	1
	*Diagramma pictum**	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	1
Labridae	*Halichoeres nigrescens*	0	1	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0
	Halichoeres kneri	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	Choerodon sp.	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
Latidae	*Psammoperca waigiensis*	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	1
	*Lates calcarifer**	0	1	1	0	1	1	0	1	1	0	0	1	0	0	0	1	1	1
Lethrinidae	*Lethrinus lentjan**	0	0	1	0	1	0	0	1	1	0	0	0	0	0	0	0	1	1
	Lethrinus genivittatus	1	1	0	1	0	1	0	1	1	1	1	0	0	0	0	1	1	1
Lutjanidae	*Lutjanus argentimaculatus** ∆	0	0	1	1	1	1	1	1	1	0	0	1	0	0	1	1	1	1
	*Lutjanus fulviflamma** ∆	0	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0	1	1
	*Lutjanus fulvus**	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	*Lutjanus johnii**	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	*Lutjanus lemniscatus**	1	0	1	1	1	1	0	1	1	0	0	0	0	0	0	0	0	0
	*Lutjanus rivulatus**	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	1
	*Lutjanus russellii** ∆	0	0	1	1	1	1	1	1	1	0	0	1	0	0	1	0	1	1
Megalopidae	Megalops cyprinoides	0	1	0	1	0	0	0	1	1	0	0	0	0	0	0	1	1	0
Monacanthidae	Monacanthidae	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1	1
Monodactylidae	*Monodactylus argenteus*	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1
Mugilidae	*Liza subviridus*	0	1	0	0	0	1	1	1	1	0	1	0	0	0	1	1	1	1
	Liza vaigiensis	0	1	0	0	0	1	0	1	1	0	0	0	0	0	1	0	1	0
	Mugil cephalus	0	1	1	0	0	1	0	1	1	0	1	0	0	0	1	1	1	0

Family	**Species**	Seagrass	Open Bottom	Woody Debris	Creek Rock	Embayment Rock	Mangrove	PZ: Upstream	PZ: Creek	PZ: Embayment	Seagrass	Open Bottom	Woody Debris	Creek Rock	Embayment Rock	Mangrove	PZ: Upstream	PZ: Creek	PZ: Embayment
	Valamugil buchanani	0	1	1	0	0	0	1	1	1	0	0	0	0	0	0	1	1	1
Nemipteridae	*Pentapodus sp.**	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	*Scolopsis sp.**	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
Platycephalidae	Platycephalus fuscus	1	1	0	0	1	0	0	0	1	1	1	0	0	0	1	0	1	0
Pomacentridae	*Chrysiptera unimaculata*	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	Chrysiptera unimaculata	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	Neoglyphidodon melas	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	Neopomacentrus azysron	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	Neopomacentrus bankieri	0	0	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	1
	Neopomacentrus teniuris	0	0	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	Abudefduf bengalensis	0	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0
Scaridae	*Scarus sp.**	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
Scatophagidae	*Scatophagus argus*	0	1	1	1	1	1	0	1	1	0	0	0	0	0	1	0	1	1
	selenotoca multifasciata	0	0	1	0	0	1	0	1	1	0	0	0	0	0	1	0	1	1
Scombridae	*Scomberomorus sp.*	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1
Serranidae	*Epinephelus coioidies**	0	1	1	0	1	1	0	1	1	0	0	1	0	0	0	0	1	0
	*Epinephelus malabaricus**	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	1	0
Siganidae	*Siganus fuscescens*	1	0	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	1
	*Siganus javus** Δ	0	0	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	1
	*Siganus lineatus**	1	0	1	1	1	1	0	1	1	1	0	0	0	0	0	0	1	1
	Siganus spinus	0	1	0	0	1	0	0	1	1	0	0	0	0	0	0	1	1	1
	Siganus virgatus	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1
Sillaginidae	*Sillago analis*	0	1	0	0	0	1	0	1	1	0	1	0	0	0	1	0	1	1
	Sillago ciliata	0	1	0	0	0	1	0	1	1	0	1	0	0	0	1	0	1	1

Family	Species	Seagrass	Open Bottom	Woody Debris	Creek Rock	Embayment Rock	Mangrove	PZ: Upstream	PZ: Creek	PZ: Embayment	Seagrass	Open Bottom	Woody Debris	Creek Rock	Embayment Rock	Mangrove	PZ: Upstream	PZ: Creek	PZ: Embayment
	Sillago sihama	0	1	0	0	0	1	0	1	1	0	1	0	0	0	1	0	1	1
Sparidae	*Acanthopagrus pacificus** Δ	0	1	1	1	1	1	0	1	1	0	1	1	0	0	1	0	1	1
	*Acanthropagrus australis** Δ	0	1	1	1	1	1	0	1	1	1	1	0	0	0	1	0	1	1
Sphyraenidae	*Sphyraena barracuda*	0	1	0	0	0	1	0	1	1	0	0	0	0	0	1	0	1	1
	Sphyraena obtusata	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Terapontidae	*Helotes sexlineatus**	1	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1
	Mesopristes argenteus	0	0	1	0	0	0	1	1	0	0	0	0	0	0	1	1	1	1
	*Pelates quadrilineatus**	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	1	1
	*Terapon jarbua**	1	1	0	0	1	1	0	1	1	0	1	0	0	0	0	1	1	1
	*Terapon puta**	1	1	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	1
	*Terapon theraps**	1	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0	1	1

4.1.1 Species-specific detail

Lutjanus russellii: our results corroborate earlier findings that this species uses both mangroves and woody debris habitat, but adds rock habitat in upstream, creek and embayment process zones.

Lutjanus argentimaculatus: our results corroborate earlier findings that this species uses both mangroves and woody debris habitat, but adds rock habitat in upstream and creek process zones.

Caranx species: our results corroborate earlier findings that this group uses both mangroves and open bottom habitat, but adds rock habitat in upstream, creek and embayment process zones.

Acanthopagrus species: our results corroborate earlier findings that this group uses mangroves and adds rock habitat in upstream, creek and embayment process zones. However, our occurrence data differs from earlier findings that suggest early juveniles are predominantly found in seagrass. Instead we found early juveniles predominantly in mangrove forests and woody debris.

Pomadasys species: our results add many new structured habitat types to this group's occurrence patterns, and show that the two most common speies (*P. argenteus* and *P. kaakan*) predominantly use the upstream and creek process zones.

4.2. The relative fisheries values of different habitats

4.2.1 Open habitats

Open bottom habitats in embayments appear to be of relatively low fisheries value per unit area. Fish of any kind were rarely encountered there, as revealed in univariate CART analysis. Moreover, fish that were encountered were generally of low fisheries value. Groups such as mugilids and *Gerres* spp. did occur frequently in these habitats, but were encountered more frequently in other habitats, particularly seagrass. Species that were only found in open bottom habitat include *Siganus virgatus* and *Sphyraena obtusata,* both of which can be considered 'vagrant' species not typically encountered in the near-shore coastal zone. While this habitat may still hold value for many fish populations, it is by far the least valuable per unit area. However, it is also by far the most widely available habitat by area (as indicated by our preliminary analysis of acoustic benthic imaging, in preparation), so its large areal extent means the aggregate value of this habitat may well be considerable.

Despite its apparent low value per area, specific areas of open bottom are likely to be crucial to ecosystem functioning, when their wider ecological roles are considered and when viewed as dynamic rather than static entities. Because they dominate total habitat area, open habitats form the matrix in which other habitats are embedded and so act as critical corridors that link other more valuable habitat types. As our results from this coastal system and findings elsewhere suggest, very few species are confined to a single habitat type or process zone (Nagelkerken 2007). Fish travel between habitats during the course of their daily foraging and shelter seeking behaviours, and throughout the realisation of their in life cycle strategies (Baker et al. 2013, Olds et al. 2013). Therefore, in some particular areas the preservation of open habitat may be critical to ensure free passage between habitat patches. In addition, valuable habitat that is both ephemeral and hard to detect may occur in these areas. Habitat such as seagrass beds which change patch size and location constantly (Coles et al. 1993) can periodically invade areas of otherwise bare open habitat, changing its value for fish. Rare soft sediment sponge and ascidian communities also occur patchily in coastal open bottom areas (Alongi 1989) but in many areas have been destroyed due to bottom trawling (Watling and Norse 1998). Consequently, many open bottom habitat areas that in the past harboured rich biogenic communities have the potential to regain high fisheries value if reduction in disturbance allows the recovering of these communities.

4.2.2 Structured habitats

Areas of large complex structure were valuable to a wide range of species, regardless of the type of structure. A large portion of coastal fish fauna can be conceptualised as a community of structure-associated fish with varying ability to exploit intertidal waters and to move between process zones. To a large extent, it is the structure's position in the seascape that determines to whom it is valuable, rather than the qualities of the structure itself. Wherever structured habitat occurs, it will be utilised. This supports the pervasive idea of the high value of structurally complex habitats in marine ecosystems (Laegdsgaard and Johnson 2001, Heck et al. 2003, Gratwicke and Speight 2005). In keeping with these notions, species diversity and overall fish presence sharply dropped off in areas where structure size was smallest: cobble in the case of rock, FWD and LCWD in the case of woody debris, and ESI in the case of free living sessile invertebrates.

Woody debris habitat is of particular value to fisheries species (Boyer 2003, Kaeser and Litts 2008). Nearly all common fisheries species in our study system use this habitat, as it is available to both the intertidal mangrove associated components and subtidal rock associated components of the fauna. Additionally, both the mangrove jack *Lutjanus argentimaculatus* and the grunters *Pomadasys argenteus* and *P. kaakan* were concentrated there. In a contrasting situation to open habitat, woody debris habitat is not only particularly important to the widest variety of fisheries species, it is also quite rare in terms of area (as indicated by our preliminary analysis of acoustic benthic imaging, in preparation). The high occupancy rates of woody debris underlines the importance of riparian vegetation, such as mangroves, for snag generation (Boyer 2003) and the importance of seasonal floods that deliver fallen trees to downstream and estuarine areas.

Mangrove habitat has high fisheries value, but this value may be concentrated on the seaward edge of the forest. Only the first two meters of the seaward fringe of mangrove forests were sampled in this study, and the habitat relationships described cannot be extrapolated to the total area of the forest. Indeed, work in our area (Sheaves et al. 2016) suggests the species that use mangrove forests do not distribute themselves evenly throughout the forest, and that the highest diversity and abundances are found along the seaward edge.

Throughout all analyses, rock habitat emerged as important for coastal fauna (Fig. A2-10). Depending on which process zones that rock habitat occurs in, it is used by different components of the fauna. In both process zones, rock habitat has been undervalued as fish habitat (Table A2-6). In the creek process zone, it has rarely been mentioned as a habitat type in the literature, but it provides habitat for the same taxa that use woody debris and mangrove forests at high tide, as well as for rock-associated taxa that also use rock habitat in the embayment process zone.

In the embayment process zone, the particular mix of species using rock habitat is not a predictable extension of creek process zone habitat relationships, and appears to represent a previously unrecognised inshore rocky fauna. This assemblage is composed of species found in adjacent estuarine habitats (Sheaves 1995, Russell and McDougall 2005) and nearby coral reefs (Ackerman and Bellwood 2000), and represents the spatial coincidence of what are commonly thought to be two separate faunas. This is likely the case in many estuaries and embayments throughout northern Australia where rock habitat is present. A similar situation has been reported in the Gazi and Kosi estuarine systems on the east coast of Africa. The presence of a large proportion of marine, coral reef associated species in these estuaries has been attributed to areas of rocky reef that occur within their lower reaches (Blaber 2008).

While studies of these estuaries did not specifically investigate fish associations with rocky habitat (Blaber 1978, Kimani et al. 1996), they do suggest similar effects of habitat on fish fauna as this present study.

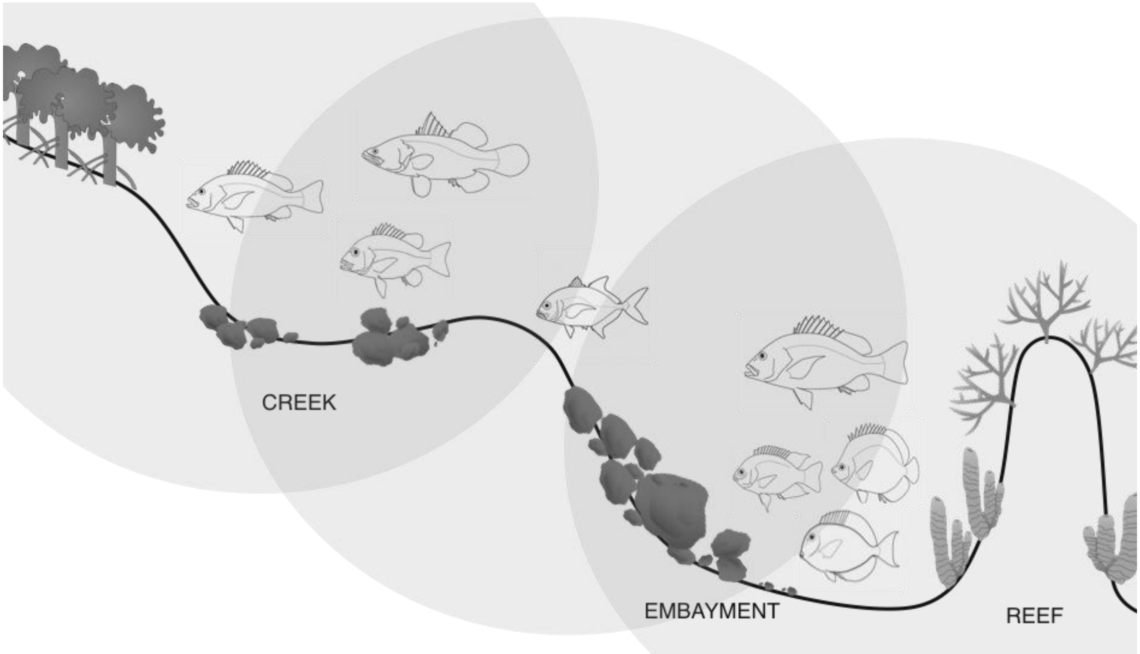

Figure A2-10. Conceptual diagram of the roles that rock habitat plays for different components of coastal fauna depending on location. When present in the creek process zone, it provides complex structured habitat for fish using the creek and surrounding mangrove forest at high tide. When present in the embayment it provides complex structured habitat for marine, reef associated fish. In both process zones, rock provides complex structured habitat for estuary fish that utilise both process zones.

While seagrass habitat was found to be used less broadly by coastal fauna, it seems to be an important nursery habitat for some taxa. It appears that seagrass habitat is unable to fulfil the requirements of larger juveniles, particularly of the *Lutjanus* genus, for large complex structure. However, it is useful to early juveniles. *Lethrinus genivittatus* and the Teraponid group had strong associations with seagrass, along with *Siganus fuscescens*. These three taxa were only present in the survey region as early juveniles. Additionally, seagrass was the habitat where the most settlement hotspot activity was recorded.

4.3. The importance of habitat linkages

4.3.1 Mangrove-woody debris complex

The overlap in fish-habitat relationships between mangroves and woody debris highlights an important aspect of the Australian mangrove forest function. Much attention has been given to the fisheries and nursery values of mangrove habitats globally. However, along meso- and macro-tidal coastlines, these areas are only available to nekton when inundated (Baker et al. 2015), so fish must spend a large proportion of their time in sub-tidal areas of estuarine and near-shore habitats (Laegdsgaard and Johnson 1995, Sheaves 2005, 2009). Thus, the habitats used at these times must be at least as important for nursery functioning as the better studied intertidal mangrove areas (Johnston and Sheaves 2007). Meso- and macro-tidal forces have another effect: that of woody debris generation. Large volumes of water move in and out of tidal creeks and channels on a daily basis, redefining water courses, developing erosional/deposition banks and undercutting sections of mangrove forest. This leads to a constant and reliable generation of woody debris that is enhanced by upstream forest inputs during flood or storm disturbance events (Boyer 2003, Kaeser and Litts 2008) and provides important subtidal habitat to nekton that use the living forests at high tide. The tight causal relationship between tides and woody debris allows for ecological adaptation and specialisation. Woody debris habitat in these systems is best viewed as a continuation of mangrove habitat into the subtidal realm, as the weight of evidence suggests in our multivariate analysis and analysis of common species habitat relationships (Fig. A2-4, Fig. A2-7).

Given the interconnected nature of mangrove and woody debris as fish habitat, the absence of either is likely to diminish the value of each. The absence of suitable sub-tidal structured habitat can preclude the use of particular intertidal areas for some fish (Irlandi and Crawford 1997, Sheaves 2005). In other systems, the extent of feeding by mobile sub-tidal predators in intertidal areas can be contingent on the occurrence of suitable habitats in the seascape (Rilov and Schiel 2006). A particularly well studied species from within our system, *Lutjanus argentimaculatus* is a specialised consumer of sesarmid crabs, which feed on mangrove leaf-litter within mangrove forests. This species links mangrove forests and sub-tidal areas trophically through the export of mangrove productivity as they move from mangrove forests to low tide refuges (Sheaves and Molony 2000). Nine common fisheries species had a substantial presence in both habitats (Table A2-4). By facilitating these kinds of interactions, the presence of certain sub-tidal habitats can promote or inhibit linkages between different areas of the seascape, which can in turn alter the movement of productivity through coastal ecosystems and into fisheries stocks.

4.3.2 Life stage specific habitat utilisation

There are differences in habitat occupancy patterns for different life stages of many common fisheries species. Conceptualised as a ‘nursery seascape’ (Nagelkerken et al. 2015), coastal areas are thought to provide a nursery function as a whole, with different habitats and areas important for different stages of fish development. As an individual grows and its requirements change, it moves between different habitats. Therefore, nursery function is provided at the system level, while individual habitat components and the links between them are each discretely important for different reasons. Maintaining this chain of habitats is crucial to the continuing viability of fish populations (Nagelkerken et al. 2015).

The earlier stages of a fishes’ life history, and the first links in these habitat chains, are the most critical in determining recruitment but also the least understood by scientists and managers. The many larger juvenile predators in these coastal nurseries are known to prey on small recruits (Baker and Sheaves 2009), and may exert a structuring force in arguably the most significant population bottleneck in a fish’s life-history (Searcy and Sponaugle 2001, Chambers and Trippel 2012). Whether the importance of early juvenile habitat occupation is determined by the fish themselves through selection (McDermott and Shima 2006), or through differential predation among early juvenile habitats (Juanes 2007), access to appropriate habitat can mediate mortality during this critical period (McCormick and Meekan 2007). Unsurprisingly then, for many organisms, habitat requirements are most specific during the early juvenile phase (Langton et al. 1996). In better studied systems such as coral reefs, most early juveniles have specific habitat requirements (Öhman et al. 1998). Our results show a similar tendency for coastal fisheries species. Lutjanids, sparids and lethrinids tended to have highly specific early juvenile habitat requirements, and more general habitat requirements as late juveniles. These ontogenetic steps are common around the world, especially within the lutjanids, but the habitat requirements are often highly specialised and species specific (Russell and McDougall 2005, Tanaka et al. 2011, Berkstrom et al. 2013). These early juvenile habitat relationships are likely to be the most crucial in maintaining population viability (Caddy 2008).

4.4. The functions of different process zones

4.4.1 Open habitat

Open soft sediment habitat can be of low per-unit-area value when present in embayments, but have substantial per-unit-area importance when they occur in creeks or upstream reaches. CART analysis revealed that while only 30% of samples from open habitat in embayments contained fish, fish occurred in 50% of samples from open habitats in creeks and upstream areas. In general, the assemblage found in open bottom areas lacked many of the taxa that dominate this habitat in shallower areas. In the intertidal and immediate subtidal it contains a rich and specialized fauna including Sillaginidae and Ambassidae (e.g. Sheaves 2006). This contrasts with the depauperate fauna in deeper open bottom habitats, observed for fish in this study, and benthic invertebrates (Sheaves et al. in review). For fish in estuaries, open habitats may be of lower fisheries value when they occur sub-tidally rather than inter-tidally. In addition, open habitat in creeks contained the largest proportion of settlement hotspots identified in this study, and may provide important nursery functions for early juveniles.

4.4.2 Structured habitat

In general, there appears to be important downstream ontogenetic progression through process zones in nursery function. *Lutjanus russellii* early juveniles were found concentrated in rocky habitat upstream and in creeks, and later juveniles spread more generally between structured habitat types but with the largest concentration in rocky habitat in embayments. *Lutjanus argentimaculatus* early juveniles were concentrated in upstream woody debris, and later juveniles were spread throughout a variety of structurally complex habitat types within the creek process zone.

4.5. Conclusion

The identification and delineation of habitat types that have a fundamental effect on the characteristics of faunal assemblages is crucial in understanding the ecological support systems that underpin fisheries production. Our results show a tendency for coastal fisheries species to have highly specific early juvenile habitat requirements, and more general habitat requirements as late juveniles. In general, this ontogenetic progression appears to flow downstream through one or more process zones.

5. Implications and recommendations

The six ecologically meaningful fish habitats determined and described in this study can be used to effectively populate coastal habitat maps. These can in turn provide the basis for strategic decision making. Each fish habitat is described by a set of physical and location attributes that functionally hold different values for fish. Below, we discuss strategies for using this information to preserve the fisheries value of coastal areas.

5.1. Prioritising fish habitat

5.1.1 Low value open habitat

Open habitat in embayments is by far the least valuable per unit area, as it sparsely utilised, and largely only by species of low fisheries value. The massive areal extent (as indicated by our preliminary analysis of acoustic benthic imaging, in preparation) of this habitat indicates that despite its low per unit areas value, the aggregate value of open habitat may be considerable. The interspersion of other habitat types within the open bottom matrix means it provides critical connectivity pathways for fish that utilise multiple habitats, which in this system includes all common fisheries species. A slight reduction in the area of this habitat available to fish may be of minimal impact. However, if accompanied by a reduction in connectivity, the impact may be significant. In addition, valuable habitat types that are ephemeral or difficult to detect can occur in these areas. Therefore, caution should be taken in areas of proposed disturbance. Monitoring should be carried out to determine the utilisation of the area as a connectivity pathway, and specialised habitat surveys including visual surveys performed by a diver or ROV should be carried out to detect the presence of valuable habitat types.

5.1.2 Maintaining diversity

One strategy for maintaining fisheries value would be to maintain habitat diversity, ensuring the full breadth of habitat types are available along the full length of process zone types. Many fisheries species appear to have a specific set of habitat requirements, especially early juveniles. Distinct components of the estuarine fauna use distinct habitats, and there are clear links between habitats in the form of habitat complexes and nursery habitat chains. Therefore, it seems that habitat *diversity*, and in particular the diversity of *structurally complex* habitats, is important in maintaining the fisheries values of coastal and estuarine systems. In addition, late juveniles of many species appear to use a wide range of the available structurally complex habitat types. Therefore, all types of structured habitat are valuable both for their specific qualities as early juvenile habitat, and in general as late juvenile habitat. The process zone where a habitat occurs can change the species that use it and how much it is used. Therefore, to maintain function, the breadth of naturally occurring habitat types should be maintained in each process zone, along with the connectivity between them.

5.2. Offsetting and replacing lost functionality

In general, caution should be used when interpreting the results of this study that pertain to fisheries habitat values. While it can be vitally important to maintain fish-habitat relationships (Beck et al. 2001), value can also be conferred at the ecosystem scale (Sheaves 2009, Sheaves et al. 2016). Restoration activities, even if they achieve their stated aims of replacing certain functional components, rarely achieve full ecosystem functioning (Maron et al. 2012).

5.2.1 maintaining and supporting habitat linkages

An important finding of this study is the tight link between mangrove forests and woody debris in terms of habitat function. It suggests that when either habitat is to be offset, it should be both present and available to fish in the offset area. Mangrove forest lining a structure free, dredged channel is unlikely to provide the breadth of fisheries values detailed in this study. Similarly, subtidal structure where there is no access to intertidal forest is unlikely to have the same values as found in this study. Given the many complex sets of habitats relationships identified in this study, offsetting may need to focus on mosaics of habitats rather than single habitat types, especially for maintaining the value of creek rock and seagrass. However, the scale at which these linkages operate is yet to be determined, and would be an important avenue for future fisheries research.

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Annexes

Annex Table 1. Sample size for each dominant biota category for each depth band within each site

Depth:	0-2m	2-4m	4-6m	6-8m	8-10m	10-12m	12-14m	14-16m	16-18m	18-20m	Grand Total
creek	9	274	70	12							365
algae		26	6	2							34
bare	6	97	53	4							160
debris		2									2
ESI	1	4	3	3							11
FHCWD		6	2								8
FWD		1									1
HCWD		19		1							20
LCWD		8	5								13
mangrove	2	100									102
seagrass		11	1								12
SFSI				2							2
embayment	1	210	164	110	103	81	65	19	7	3	763
algae		61	51	20	9	4	2	1	2		150
bare	1	109	70	71	59	60	50	13	5	3	441
bioturbation		1	6	2	6	1	1				17
debris		2	2	1	1	1					7
ESI			5	9	14	7	6	2			43
FHCWD		2									2
FWD		1									1
HCWD		3									3
LCWD		4	1	1		1					7
macroalgae			6	2		1					9
seagrass		27	22				1				50
SFSI			1	4	14	6	5	3			33
upstream	1	42	22								65
algae		14	4								18
bare		11	8								19
debris		1									1
FHCWD		9	6								15
HCWD		5	3								8
LCWD	1	2									3
mangrove			1								1
Grand Total	**11**	**526**	**256**	**122**	**103**	**81**	**65**	**19**	**7**	**3**	**1193**

Annex Table 2. Sample size for each substrate texture category for each depth band within each site

Depth:	0-2m	2-4m	4-6m	6-8m	8-10m	10-12m	12-14m	14-16m	16-18m	18-20m	Grand Total
creek	9	274	70	12							365
boulder	1	16	3	3							23
cobble		14	5								19
gravel		3	3	1							7
mud	2	137	31	1							171
sand	6	94	23	3							126
shell grit		10	5	4							19
embayment	1	210	164	110	103	81	65	19	7	3	763
boulder		18	38	23	27	13	11	4	2		136
cobble		9	16	10	8	4	5	5		1	58
gravel		4		1	2		5		1	1	14
large boulder		8	3	6	1	2					20
mud		90	73	56	57	46	29	3	1		355
sand	1	73	27	11	4	8	4				128
shell grit		8	7	3	4	8	11	7	3	1	52
upstream	1	42	22								65
boulder		12	4								16
cobble		5	1								6
gravel		6	1								7
large boulder		2									2
mud		7	3								10
sand	1	10	13								24
Grand Total	**11**	**526**	**256**	**122**	**103**	**81**	**65**	**19**	**7**	**3**	**1193**

Appendix 3. Identifying Fish-Habitat Relationships using Catch and Satellite Data

Martha Brians and Marcus Sheaves

Executive Summary

Tropical coastal habitats are often associated with high fish abundance and productivity. For example, the Hinchinbrook region contains extensive fish habitats, making it one of the most popular recreational fishing locations in north Queensland. It also plays a role in the translocation of nutrients and fish to the Great Barrier Reef, with a number of key fisheries species relying on Hinchinbrook's estuarine habitats for part of their lifecycles. Consequently, understanding habitat use by fish in areas like Hinchinbrook Channel is a necessity for effective management. However, habitat analysis on a large scale can be time consuming and produce results that are difficult to interpret and translate. This project develops and tests a new approach of 'Habitat Identification by Catch and Satellite Data' (*Habitat IDxCSD*), using the Hinchinbrook region as a case study. The *Habitat IDxCSD* approach uses open-access satellite data, cross referenced with a large-scale public data set in a desktop analysis. While there are some limitations, this unique approach has the potential to be developed into an effective decision support tool to improve the management of coastal fishery habitats. The *Habitat IDxCSD* approach identifies key fish-habitat relationships and allows the extraction of valuable habitat information to inform management decision making. Further, development is required before the approach can be operationalised as a valid method of fish-habitat assessment.

1. Introduction

1.1. Background

Tropical coastal habitats are often associated with high fish abundance and production. Habitats including mangroves, seagrass, and snag-filled creeks are important nursery grounds and areas for fish feeding and protection. However, the further investigation of these broad statements often reveals many gaps in research and understanding (Sheaves et al. 2015). How often do key recreational species actually use mangroves for shelter? Which commercial species utilise seagrass as an optional versus mandatory nursery ground? Researchers around the tropics are addressing the suite of questions that will bring us a more complete understanding of fish and the habitats they use. However, addressing each of these questions takes time, and the use of tropical coastal habitats and the management of these species does not wait for complete answers. Therefore, in the pursuit of long-term sustainability, managers are required to make informed decisions based on available information (Beck et al. 2001).

Research-informed management is often a haphazard process, where pieces of data and resources are gathered together from a diversity of sources and surmised into broader conclusions. Almost invariably, this includes data that relate to a diversity of locations, often very distant from the unit to be measured. This process is not ideal; drawing data from diverse and spatially disparate sources brings with it a high likelihood that some, or many of the conclusions drawn will be inaccurate, and the resultant management decisions inappropriate. The alternative of conducting extensive on-ground research is usually impractical because it is both very time consuming and prohibitively expensive. Moreover, the cost structure of detailed research means that most intensive on-ground studies are constrained to investigate only few selected sites. This provides a poor match with the needs of management that requires decision making that is relevant to large spatial scales. Consequently, there is a clear need for cost-effective approaches that provide understanding specific to the area to be studied and so addresses location-specific fish habitat management more directly. Such approaches should be specific to the area to be managed, relate to the scale at which management will be applied, be referenced to freely available geospatial data and utilise opportunistically available, location-specific biological information (Dale et al. 2010).

This study takes the first step in developing an approach for investigating fish-habitat utilisation at a whole-of-system scale by cross referencing open-access satellite data with a large-scale public data sets collected by recreational anglers. While there are some limitations, this unique approach has the potential to provide understanding that is not available from traditional fisheries studies and so has the potential to be developed as a decision support tool to improve the management of coastal fish habitats.

1.2. Study Site

The Hinchinbrook region contains over 500 km^2 of estuarine, freshwater and coastal fish habitats, making it one of the most popular recreational fishing locations in north Queensland (van Riper et al. 2012). It is the site of intense biological processes and plays a vital role in supporting the greater Great Barrier Reef ecosystem by acting as an upload site for terrestrially derived nutrients into marine food webs and in providing key nursery and feeding grounds for the many species that rely on the estuarine habitats during parts of their lifecycles. Consequently, the Hinchinbrook region is of particular interest to coastal managers making it a prime site for the development of new management-focuses fish/habitat assessment approaches. Additionally, because of its popularity as a recreational fishing site, extensive, spatially explicit fish catch data sets are available in the form of amateur fish tagging records are available to populate the model.

1.3. Objectives

This project develops and evaluates a new approach of 'Habitat Identification by Catch and Satellite Data' (*Habitat IDxCSD*), using the waters of the Hinchinbrook area as a case study (Fig. A3-1). The method involves using Google Earth satellite imagery to identify habitats at the scale of fish occurrence reports in a large, archived data set. In this case the fish occurrence data takes the form of angler tagging catch-and-release data, but the method could equally be applied to data collected by governments, fishing organisations, or in citizen science projects. This provides two robust data sets that can be aligned and analysed at a management-relevant scale.

The three main objectives of this study were:

1. To develop and test the approach '*Habitat IDxCSD*';
2. Using the *Habitat IDxCSD* to identify important fish habitats in the Hinchinbrook Channel for key fish species;
3. Use targeted surveys of expert anglers to cross-validate outputs from the *Habitat IDxCSD* methodology.

2. Methods

2.1 Developing the Habitat IDxCSD

2.1.1 Approach

The method *Habitat IDxCSD* was developed specifically for this project, with the intention of developing the technique for future use in management and robust research.

The method involves combining satellite spatial imagery with fish catch data sourced from large scale public data sets held by government entities, fishing organisations, and universities. These data need only include fish species identification and the GPS of catch location to be useful in the methodology, but additional information that is available can also be utilised.

The data set used here, InfoFish tag-and-release data (Fig. A3-1), consists of capture records of species recorded in 1km^2 GPS grid cells. This provides the citizen science angler with anonymity as to the specific fishing site, while supplying catch data defined at a spatial scale that can be linked to habitat characteristics of the grid unit that are easily identifiable in the satellite imagery, such as creek junctions and areas of boulders. This 1km^2 scale is also relevant to management; it is difficult to develop management actions to apply at smaller scales, so greater detail is of limited value, and larger scales cannot provide the habitat specific resolution needed for effective management.

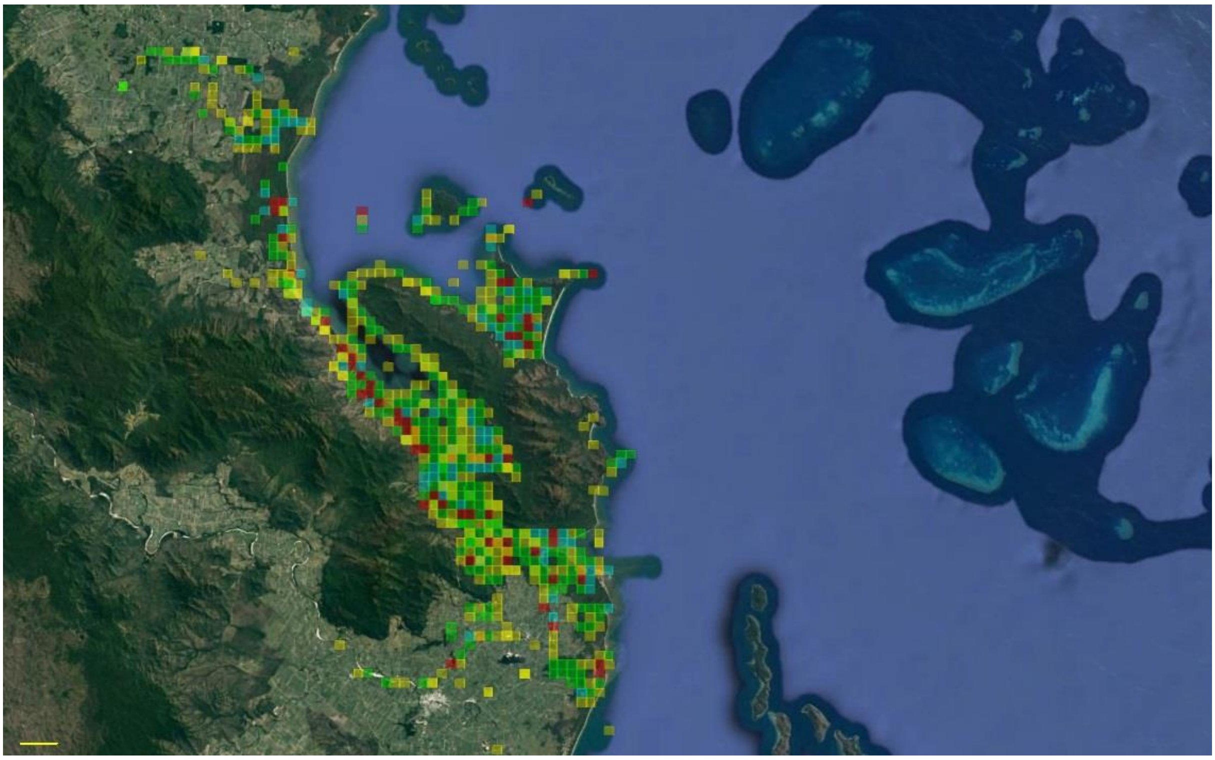

Figure A3-1. The Hinchinbrook region with 1km grid cell representation of the InfoFish data; scale bar 4km.

The habitat classifications used were defined so they were (i) detectable from satellite imagery, (ii) cross-compatible to other tropical studies, and (iii) recognised as units likely to be differentially utilised by particular fisheries species.

2.1.2: Fish tag data

The fish tag data used in this analysis was purchased from InfoFish Australia. The dataset includes 30,147 data records of fish tagged and released in the Hinchinbrook region (Fig. A3-1), across 28 years (1985 – 2013), and includes a total of 105 species. The full data set contained 602 grid cells and 100 of these were randomly selected for use in developing the *Habitat IDxCSD* approach. Due to the range of uncertainties involved (noted below under limitations), rather than using the number of presences pre grid cell, fish presences per grid were used as a more robust measure of utilisation.

2.1.2.1 Target species list

Of the 105 species included in the initial data collection, 14 of these were selected for this study, meeting two criteria: 1) high data volume and 2) a species of interest (sportfishing, management, or knowledge deficient) (Table A3-1).

Table A3-1. Fish species used in the Habitat IDxCSD analysis.

Number	Scientific Name	Common Name	Tagging accounts
1	*Lates calcarifer*	Barramundi	1442
2	*Pomadasys kaakan*	Barred Javelin	912
3	*Epinephelus malabaricus*	Blackspotted Rockcod	607
4	*Eleutheronema tetradactylum*	Blue Threadfin	128
5	*Lutjanus erythropterus*	Crimson Snapper	733
6	*Platycephalus fuscus*	Dusky Flathead	100
7	*Caranx ignobilis*	Giant Trevally	230
8	*Lutjanus johnii*	Golden Snapper	115
9	*Epinephelus coioides*	Goldspot Rockcod	1346
10	*Lutjanus argentimaculatus*	Mangrove Jack	1222
11	*Acanthopagrus pacificus*	Pikey Bream	1463
12	*Lutjanus malabaricus*	Saddletail Snapper	469
13	*Hephaestus fuliginosus*	Sooty Grunter	211
14	*Pomadasys argentius*	Speckled Javelin	240

.

2.1.3: Habitat classifications

Thirteen habitat categories were established to correspond with management relevance and be identifiable by satellite imagery (Table A3-2, Fig. A3-3).

Table A3-2. Habitat categories used in the Habitat IDxCSD analysis.

	Habitat	Definition
1	Vegetated Bank	Vegetation lining waterways. In saltwater areas this is almost exclusively mangroves but these are replaced by rainforest riparian vegetation in freshwater areas
2	Creek	Water ways with width above 15m that are offshoots of the main Hinchinbrook Channel, the coast, or of another creek.
3	Drain	Small, short waterway entering creek, channel or coast, less than 15m wide
4	Junction	The mouth of a creek (at channel or coast), or the meeting of two or more creeks
5	Tidal Sand	Intertidal sand that can be seen from satellite imagery
6	Creek Upstream	Smaller width (less than 15m) and the upstream portion of a creek
7	Channel	The main Hinchinbrook Channel
8	Coast	Mainland coast above and below the channel (18°31'34.84"S, 146°20'29.39"E); (18°13'51.92"S, 146° 1'14.96"E)
9	Artificial Structure	Artificial structure extending into the waterway (bridges, jettys, docs, etc.)
10	Island	Small islands with no land connection (not including Hinchinbrook Island)
11	Open Water	Water that is not bound by land (not including Hinchinbrook Channel)
12	Boulders	Rocks and boulders along the water’s edge visible by satellite imagery
13	Farming	Farming land neighbouring a waterway

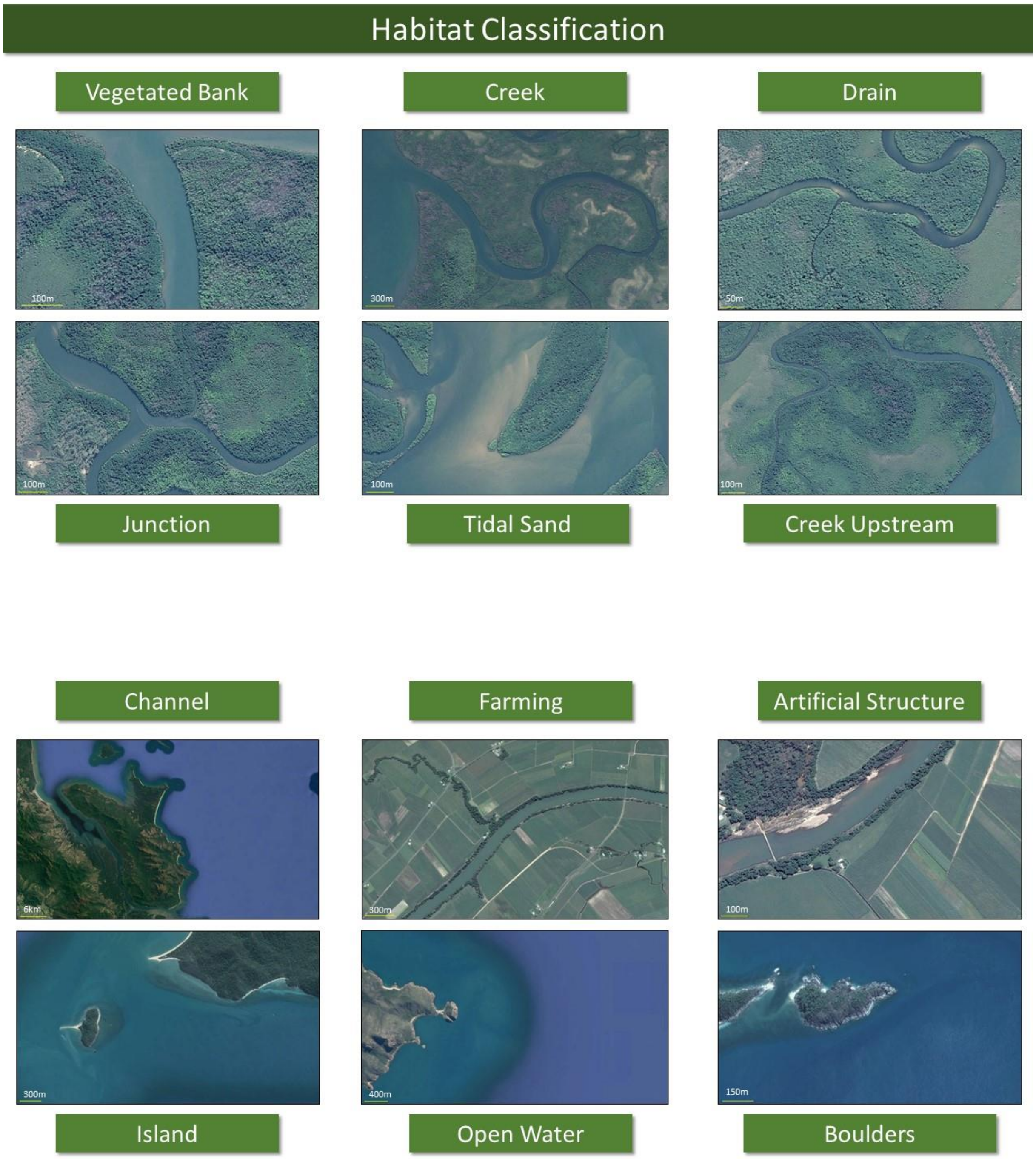

Figure A3-2. Pictorial examples of habitat classifications in Table A3-2.

2.1.4 Grid cell analysis

High catch grid cells were identified from the master dataset, and each key grid cell was analysed for habitat attributions and the presence of each species. This information was then evaluated for the percentage of units that contained each habitat type in which each fish species was captured. The analytical output was translated into Geographic Information

System (GIS) to provide a multi-layer suite of information. This GIS output was consolidated into two ‘Habitat Matrices’ aimed at providing simple look-up tables tools to communicate information on key habitats used by different species.

2.1.6 Limitations

2.1.6.1 Limitation 1: Data reliability

Gathering fish tag data from sources such as fishing organisations can be broadly conceptualised as citizen science; a form of data collection that relies on the community to collect data. This often raises the question of data reliability, and there is often some training or guided datasheet to standardise the methods.

However, in this case, the data are likely to be relatively reliable. Anglers catch locations are only recorded at the scale of a one kilometre pixel, reducing the chance of intentional misreporting aimed at protecting fishing spots, while also reducing the impact of small spatial inaccuracies in locating the capture position. Moreover, anglers have an incentive for accurate reporting because the value of the data from tagging programs is continually emphasised by the fishing clubs that coordinate the distribution of tags. However, the value of the data still relies on seven factors that determine whether a fish will be identified from a particular location:

1. The fisher base knowledge of where to catch the species.
2. The fish being present at the time the angler is fishing.
3. The willingness of the fish to bite on bait or lure.
4. The skill of the angler at eliciting the fish to bite the bait or lure.
5. The skill of the angler in landing the fish.
6. The captured fish being in suitable condition for tag and release.
7. Chance.

Consequently, fish can only be tagged if these criteria are satisfied. Therefore, there are likely to be locations that are used by a species that are not identified in the tagging data. However, the focus of this method is on identifying habitat types associated with catches of a species, so the reliability of identifying a habitat used by a species goes up with the number of grid cells analysed.

Additionally, the uncertainty generated by these factors, along with angler behaviour that sees them return regularly to a fishing spot where they have been successful, means that data on the number of fish tagged per grid cell is of very doubtful quality. Consequently, identification of grid cell utilisation needs to be limited to presences rather than the number of fish of a species tagged.

2.1.6.2 Limitation 2: Grid cell size

The limitation with the grid cell size used is that a grid cell generally includes a number of different habitat types (e.g. Fig. A3-3). In the *Habitat IDxCSD* analysis all the habitats in a grid cell are listed as potential habitats but assessment of habitat associations is made on the basis of the proportion of cells containing a particular habitat type in which a species was recorded. For example, while some 'boulder' habitats might show up in one or two accounts for a species, a 'creek junction' may be present for all accounts. However, the less common habitat accounts for a species should not be ignored but used to indicate areas where more detailed study is needed.

Figure A3-3. Example of the variety of habitats that can be included in a grid cell, with vegetated bank, creek, junction, and drain habitats all clearly identifiable in this cell. Scale bar: 100m.

2.1.6.3 Limitation 3: Scientific understanding

While this approach can be used with relatively little scientific understanding, making it an attractive, rapid, cost-effective approach for assessing habitat utilisation, it only provides a generalised assessment that requires extensive validation before the results can be applied with confidence. This validation can, and perhaps should, take many forms. For this developmental study, angler survey data were used to assess the strengths and weaknesses of the *Habitat IDxCSD* approach.

2.2 Angler surveys

Experienced anglers (including local commercial sportfishing operators and recognised angling experts identified by members of local sportfishing club committees) were surveyed to determine their understanding of the habitat utilisation by species that they had extensive experience catching. These include both face-to-face (41 responses) and on-line (12 responses) surveys. Anglers were asked to identify the key habitats and resources used by sportfish at three spatial scales: process zones, macro-habitats and meso-habitats. The three spatial scales were defined as follows:

- The Process Zone describes the large-scale locations a species is likely to be found in along a gradient from upstream freshwater to the open sea.
- The macro-habitat is the general habitat area a species is likely to be found in within a process zone.
- The meso-habitat is the specific habitat a species uses within a macro-habitat.

At each scale anglers were asked to identify the utilisation of a variety of standard habitat variables at each scale (see Table A3-1). These habitat variables comprised a comprehensive list of habitats for each scale identifiable in the field and workshopped in a Delphi-type process by researchers and experienced anglers.

The survey results were summarised for each species. The responses were recorded only as relative rankings depending on the proportion of responses that identified a particular habitat variable as one used by the species: categories; (some) # 0-0.4; (many) # # >0.4-0.8; (most) # # # >0.8-1.0. This approach was favoured over reporting results numerically because numeric results have the potential to be erroneously equated with quantification of the importance of each habitat. In fact, these are qualitative responses so the meaning of the proportion of responses for any category is ambiguous. For instance, single response could indicate a key habitat relationship that is unknown to other anglers, while a habitat identified by most could simply relate to a commonly held, but erroneous, belief.

3. Results

3.1 Species-Habitat identification using the Habitat IDxCSD approach

Across most species the strongest habitat associations were with *vegetated banks* and *creeks,* and to a lesser extent *drains* and *junctions* (Table A3-3). Most species other than *Lutjanus malabaricus* and *L. erythropterus* were found associated at high frequency with ***Vegetated Banks***, and most species besides *L. malabaricus*, *L. erythropterus, Hephaestus fuliginosus*, *Platycephalus fuscus* and *Caranx ignobilis* were associated with ***Creeks***. *Epinephelus malabaricus, E. coioides, Pomadsys kaakan, Acanthopagrus pacificus, Lutjanus argentimaculatus*, *Pomadasys argentius, Lutjanus johnii, Eleutheronema tetradactylum,* and *Lates calcarifer* were associated with small ***Drains***, while *E. malabaricus, E. coioides, P. kaakan, A. pacificus, P. argentius,* and *Eleutheronema tetradactylum* were associated with ***Creek Junctions***. Other variables were identified as important for particular species, such as ***Tidal Sand*** for *Platycephalus fuscus* and ***Open Water*** and ***Boulders*** for *L. malabaricus* and *L. erythropterus*.

The *Habitat IDxCSD* approach also allowed identification of the frequency in which species were captured together in the same pixel (Table A3-4), suggesting similar broad habitat requirements.

Table A3-3. Fish species/habitat associations from Habitat IDXCSD analysis. Numbers in the body of the table are percentages. Fish species are those in Table A3-1 and habitat variables detailed in Table A3-2. Colour code: (Dark) > 69, (Mid) 69 < 49, (Light) 49 < 29.

	Habitats												
	Vegetated bank	Creek	Drain	Junction	Tidal sand	Creek upstream	Channel	Coast	Artificial structure	Island	Open water	Boulders	Farming
Epinephelus malabaricus	100	100	80	100	30	50	0	0	0	20	0	0	0
Pomadasys kaakan	100	90	90	80	40	20	40	0	20	10	0	0	0
Epinephelus coioides	100	100	90	90	10	60	0	0	0	10	0	0	0
Acanthopagrus pacificus	100	100	90	100	20	60	0	0	0	10	0	0	0
Lutjanus argentimaculatus	100	100	90	30	20	20	0	0	10	10	0	0	20
Pomadasys argentius	80	70	70	60	40	20	20	20	10	0	0	0	0
Lutjanus johnii	100	80	40	40	0	20	10	20	10	0	0	0	0
Eleutheronema tetradactylum	80	70	50	50	20	20	40	10	10	0	0	0	0
Lates calcarifer	90	70	60	40	30	40	30	10	10	0	0	0	10
Caranx ignobilis	100	56	33	33	33	11	33	22	11	44	33	33	0
Platycephalus fuscus	88	63	38	25	63	38	38	63	38	0	0	0	0
Hephaestus fuliginosus	100	0	83	0	17	0	0	0	17	0	0	0	100
Lutjanus erythropterus	40	20	20	10	10	10	20	30	0	20	40	40	0
Lutjanus malabaricus	30	0	10	0	10	0	0	30	0	50	70	70	0

Table A3-4. Frequencies with which species co-occurred in pixels in the Habitat IDxCSD analysis.

	Acanthopagrus pacificus	*Caranx ignobilis*	*Eleutheronema*	*Epinephelus coioides*	*Epinephelus malabaricus*	*Hephaestus fuliginosus*	*Lates calcarifer*	*Lutjanus argentimaculatus*	*Lutjanus erythropterus*	*Lutjanus johnii*	*Lutjanus malabaricus*	*Platycephalus fuscus*	*Pomadasys argentius*
Caranx ignobilis													
Eleutheronema tetradactylum	2												
Epinephelus coioides	7		2										
Epinephelus malabaricus	5		1	5									
Hephaestus fuliginosus													
Lates calcarifer	1	1	3	1									
Lutjanus argentimaculatus	1		3	3	1		3						
Lutjanus erythropterus	1			1	1								
Lutjanus johnii	2	2	3	3	2		1	1	1				
Lutjanus malabaricus		1							5				
Platycephalus fuscus	1	1		1			2			1			
Pomadasys argentius	5	1	3	2	1		1	1		2			
Pomadasys kaakan	4	2	3	2			2	1		2		1	6

3.2 Evaluation of the Habitat IDxCSD approach using angler survey data

The survey data provide a range of qualitative information on habitat data that can form the basis for data visualisations (e.g. Fig. A3-4). However, its quality and comprehensiveness is limited by the knowledge of the contributing anglers. Comparison of the *Habitat IDXCSD* habitat-use classifications to interpretations from survey data highlights a number of points.

1. The habitats identifiable in the *Habitat IDXCSD* largely align with the *Macrohabitat* scale in the survey detail, however, this concordance is incomplete largely due to an inability to resolve all the potential macrohabitats from satellite data. This means that the habitats used in the *Habitat IDXCSD* method are a subset of those used in the surveys. Additionally, some variables, such as 'Farming' that are identifiable from satellite imagery were not included in the list of survey habitats. This is largely because the survey habitats focused substantially on habitats actually used by fish, while the satellite habitat identification focuses on structures identifiable from satellite imagery rather than specifically on the habitats used by fish. These differences make comparisons of the habitat identifications from the two sources difficult (Table A3-5). It is also clear that success of the *Habitat IDXCSD* relies heavily on identification of appropriate 'habitat' variables.

Table A3-5. Comparison of habitat identification for different species from Habiat IDxCSD analysis and angler survey data. Numbers relate to habitat variable numbers in Table A3-2. Note: The species in this table do not align completely with those in Table A3-2 because the anglers surveyed did not report on all the species in the catch and release data set.

Species	*Habitat IDxCSD*	Survey
Acanthopagrus pacificus	1, 2, 3, 4, 6	1, 2, 3, 4, 6, 12
Caranx ignobilis	1, 2	1, 2, 3, 4, 6, 12
Eleutheronema tetradactylum	1, 2, 3	1, 2, 3, 4
Epinephelus coioides	1, 2, 3, 4, 6	1, 2, 3, 4, 6, 12
Epinephelus malabaricus	1, 2, 3, 4, 6	1, 2, 3, 4, 6, 12
Hephaestus fuliginosus	1, 3	1, 2, 3, 4, 6
Lates calcarifer	1, 2, 3	1, 2, 3, 4, 6, 12
Lutjanus argentimaculatus	1, 2, 3	1, 2, 3, 4, 6, 12
Lutjanus johnii	1, 2	12
Pomadasys argentius	1, 2, 3, 4	1, 2, 3, 4
Pomadasys kaakan	1, 2, 3, 4	1, 2, 3, 4

2. The fish-habitat relationships identified from the *Habitat IDXCSD* do not align completely with the fish-habitat relationships identified in the angler surveys (Table A3-5). This includes some clear mismatches. For instance, *Lutjanus johnii* is identified as

being associated with ***Vegetated Banks*** by the *Habitat IDXCSD* but in the survey data as a species restricted to subtidal areas particularly around rocky structure. These misalignments:

a. Are largely a function of the difference in habitat resolution underpinning the two methods (see point 1 above), and of the approach used to link species to habitats in the two methods (direct fish-habitat link implicit in the survey approach vs. pixel scale correlation between fish catch records and the occurrence of habitats at the pixel scale in the *Habitat IDxCSD*). Taking the particular case of *L. johnii* the *Habitat IDXCSD* is unlikely to be reliable in habitat identification because it relies on identification of above-water habitats, so inappropriate for subtidal species because it can only identify the closest above-water habitat that will usually provide a poor indication of the occurrence of subtidal habitats.

b. Emphasise the need for multiple approaches to habitat identification because both methods, and any others used, are underpinned by a range of assumptions and limitations.

4. Discussion

This is the first attempt to analyse fish habitat use at the scale of a whole tropical estuarine/coastal system the size of the Hinchinbrook area (over 500 km^2 of fish habitats). As a decision-support tool the *Habitat IDxCSD* has some attractive advantages. It allows the opportunistic use of pre-existing citizen science-collected data, both increasing the value of amateur tagging programs and providing a link to end beneficiaries of management actions. In utilising satellite imagery to identify habitats the *Habitat IDXCSD* provides a way of easily and quickly utilising large spatial data sets to analyse habitat types and large publically available georeferenced fish catch data sets to develop fish-habitat understanding at an aerial extent not previously possible.

These data sets on which the *Habitat IDXCSD* is based provide a volume of data much greater than that available from traditional scientific research surveys. This is important because there are few instances where sufficient research data are available to support the comprehensive fish-habitat identification required for effective management (Sheaves et al. 2012). This is particularly true for tropical coastal systems that generally don't have an extensive history of formal scientific research. Even in the most extensively studied tropical systems understanding is often deficient. For instance, even for the Hinchinbrook Channel and surrounding regions, that have been the focus of a number of fish-habitat studies over the last 30 years (e.g. Sheaves 1995, 2006, Johnston & Sheaves 2008), many habitats have not been assessed (Bradley et al. in press), leaving many species-habitat relationships unassessed and, in fact, the occurrence of many species not recorded.

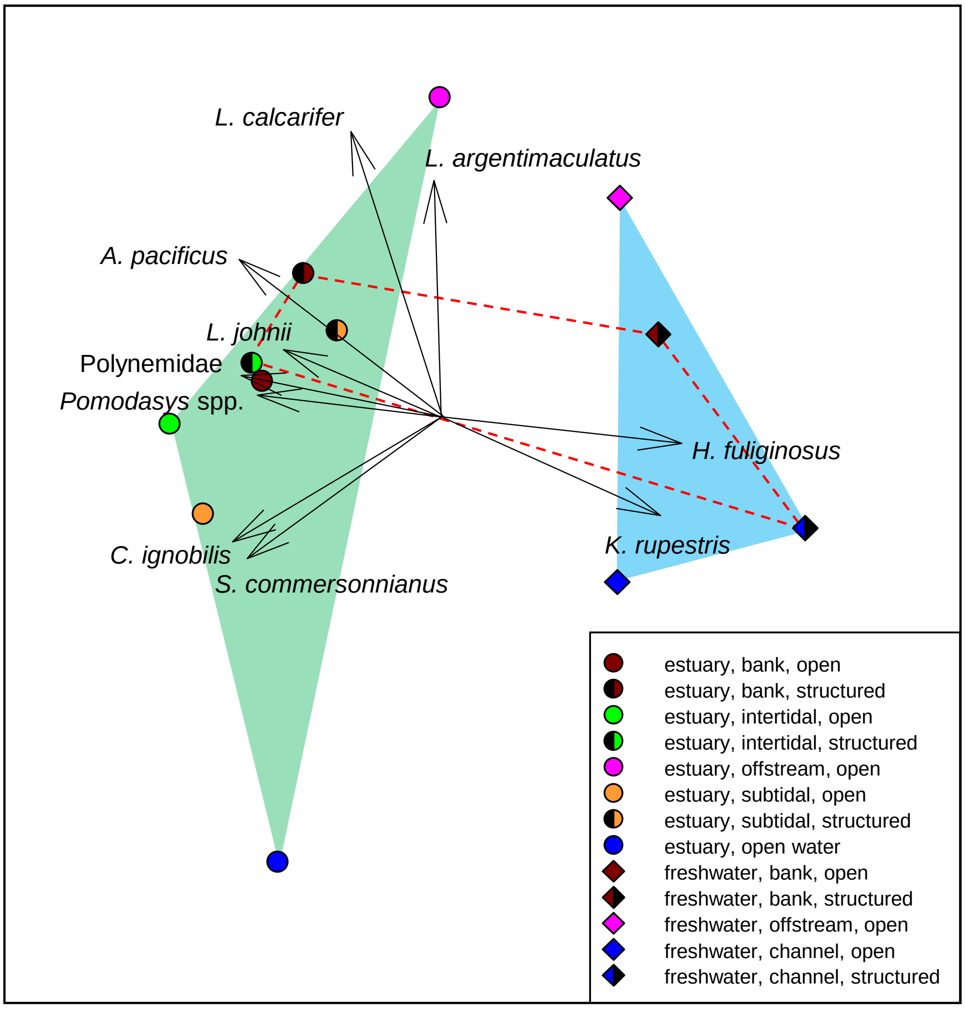

Figure A3-4. Figure 1: nMDS summary of the similarities of habitat use by fish from expert angler survey data (stress = 0.04). Species names indicate relative locations in 2 dimensional space. Vectors indicate the direction of increase in occurrence of taxa with a correlation of > 60% with the ordination space.

A further strength of the *Habitat IDxCSD* is that, by utilising angler-collected information, it focuses on the species that are most relevant to the recreational and commercial fishing industry, and so of particular value to management. In contrast, the nature of many scientific research collections means they are more focussed on the more abundant smaller species, and juveniles of larger species (Sheaves et al. 2012) – targets that are relevant to ecosystems functioning but not necessarily as directly interesting to fishers as the larger fish that they pursue.

Despite the ease of utilisation of the *Habitat IDXCSD*, its ability to be applied to large scale analysis, and its focus on species of direct interest to managers and fishers, its values need to be evaluated against its deficiencies (e.g. Table A3-6).

Table A3-6. Advantages and disadvantages of the Habitat IDxCSD method.

Advantages	Disadvantages
Easy to use	Grid cells contain multiple habitats so are not fish/habitat relationship-specific
Applicable to large spatial scales	Data reliability limited by a factors related to fish behaviour and angler skill (see 2.1.6.1)
Can fill substantial gaps not addressed by currently available research	Habitats identified from satellite or aerial imagery will not always align with the full set of habitat variables recognisable on ground
Direct focus on management-appropriate scales	Relies heavily on the identification of appropriate variables
Focuses on species of direct interest to managers/end users	Should not be used without extensive validation
Very cost and time efficient	

4.1 The way forward

Despite its limitations, the *Habitat IDxCSD* provides unique advantages that indicate that its further development is worth pursuing. Its overriding advantages are the large scale fish-habitat assessments it allows, and its focus on species of direct interest to end-users and management (Wegscheidl et al. in review). However, these advantages are null if it can't be expanded into a valid tool.

The current development study used less than 20% of the available fish catch data. This provides two possible ways forward: (i) utilising all available data to improve the habitat understanding or, (ii) testing the accuracy and value of the current understanding using the additional data. Both strategies have their advantages so it would be worth investigating each approach to determine the most advantageous option. Whichever approach is used the output clearly needs to be validated and extended by reference to other approaches. One approach is to utilise angler survey data as used here. This approach has the advantage of notionally representing understanding aggregated at the whole-of-region scale. However, it has the disadvantages of dependence on the knowledge and behaviour of anglers, and the behaviour rather than presence of fish. Consequently, it should not be used as the only source of validation. Perhaps the best approach is to utilise both methods to gain the value of the advantages of each and use the outcomes of the joint understanding to direct specific angler-independent studies using traditional sampling techniques, such as various netting approaches (e.g. Blaber 1980, Robertson & Duke 1990, Johnston & Sheaves 2008), or the rapidly developing video sampling approaches (e.g. McLean et al. 2016, Sheaves et al. 2016, Bradley et al. in press).

Most importantly, before the method is utilised for management decision support it is critical to develop a valid, best-practice methodology around it to ensure it is employed validly and its value is maximised.

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Annex Table 1: Summary of responses from face-to-face (41 responses) and on-line (12 responses) surveys of expert anglers (either commercial sportfishing operators or recognised local experts) about fish habitat use over 3 scales (Process zone; Macro-habitat; Micro-habitat). Responses are recorded only as relative rankings - these are qualitative responses so the meaning of the proportion of responses for any category is ambiguous. For instance, single response could indicate a key habitat relationship that is unknown to other anglers, while a habitat identified by most could simply relate to a commonly held, but erroneous, belief. Categories; (some) # 0-0.4; (many) # # >0.4-0.8; (most) # # #>0.8-1.0

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
total responses	34	30	21	11	38	30	15	33	16	27	23	21
1: PROCESS ZONE												
Freshwater												
Upland freshwater streams;												# # #
Lowland freshwater streams;					# # #			# # #	# # #			# # #
Floodplain freshwater wetlands;	# # #				# # #				# # #			
Estuary and transition zone												
Coastal brackish or tidal wetlands;	# # #	# # #			# # #					# # #		

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
Estuary transitional zone (the upper part of the estuary that can become low salinity during wet-season flooding;	###	###			###	###		###		###		
The main part of the estuary (mangrove line channels);	###	###	###	###	###	###	###	###	###	###		
Estuary mouth;	###	###	###	###	###	###	###	###	###	###		
Coastal zone												
Beaches;	###			###		###	###	###		###		
Headlands;	###	###	###		###	###	##	###	###	###		
Coastal reefs;		###	###	###	###	###		###	###			
Coastal zone open waters (within about 500m of coast but not beaches, sandbanks, headlands or reefs);												
Reef and offshore												
Coral reefs;		###	###		###	###		###				
Islands;		###	###		###	###		###				

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
Inter-reefal areas (outside the coastal zone and deep water among reefs);			###					###				
Offshore waters;						###		###				

2: MACRO-HABITAT

Freshwater

Rapids;											###	###
Vegetated stream banks;	###				###						###	###
Unvegetated stream banks;											###	###
Stream channels;											###	###
In-stream pools;					###			###			###	###
Lakes, lagoons, billabongs, off-stream pools;	###				###						###	
Near coffee rock;	###				###						###	###

Estuary and transition zone

Vegetated stream banks;	###	###			###		###			###		

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
Unvegetated stream banks;							# # #			# # #		
Lakes, lagoons, billabongs, off-stream pools;	# # #				# # #					# # #		
Mangrove forests;	# # #	# # #			# # #		# # #			# # #		
Intertidal mudflat;	# # #			# # #		# # #	# # #	# # #	# # #	# # #		
Intertidal sand flat;	# # #			# # #		# # #	# # #	# # #	# # #	# # #		
Intertidal rubble;	# # #	# # #	#	# # #	# # #				# # #	# # #		
Intertidal rocky;	# # #	# # #	# # #	# # #	# # #				# # #	# # #		
Subtidal rubble;	# # #	# # #	# #		# #				# # #	# # #		
Subtidal rocky;	# # #	# # #	# # #		# # #				# # #	# # #		
Steep-sided channel banks;	# # #	# # #	#		# #	# # #	# # #	# # #	# # #	# # #		
Seagrass beds;	# # #	# # #	#	# # #	# #	# # #		# # #	# # #	# # #		
Deep rocky (i.e. completely subtidal);	# # #	# # #	# # #		# #			# # #	# # #	# # #		
Shallow rocky (i.e. partly or mainly intertidal);	# # #	# # #	#	# # #	# # #				# # #	# # #		
Deep (subtidal) unvegetated open bottom;			# # #			# # #	# # #	# # #	# # #	# # #		

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
Water column (i.e. associated with surface or sub-surface waters but not necessarily associated with a particular bottom type);						###		###				
Near coffee rock;	###	###	#		###			###		###		
Coastal zone, reef and offshore												
Mangrove forest	###	###			###		###	###		###		
Seagrass beds;								###		###		
Intertidal sand flats;				###		###	###	###	###	###		
Intertidal rubble;	###	###	#	###	###	###	###	###	###	###		
Intertidal rocky;	###	###	##	###	###				###	###		
Subtidal sand flats;				###		###	###	###	###	###		
Subtidal rubble;	###	###	##		###	###		###	###	###		
Shallow subtidal rocky;	###	###	#	###	###	###		###	###	###		
Deep rocky (i.e. completely subtidal);			###						###			

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
Deep unvegetated open bottoms;						# # #	#	# # #	# # #			
Coral reef crest;								# # #				
Back reef;		# # #										
Reef lagoon;		# # #						# # #				
Coral reef slope;		# # #	# #									
Deep-water coral reef;		# # #	# # #					# # #				
Water column (i.e. associated with surface or sub-surface waters but not associated with a particular bottom type);						# # #		# # #				
Near coffee rock;	# # #	# # #	# # #		# # #					# # #		

3. Meso-habitat

Freshwater

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
In vegetation;	# # #				# # #						# # #	# # #
Alongside vegetation;					# # #						# # #	# # #
Among rocks in rapids;											# # #	# # #

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
In pools in rapids;	###										###	###
In the centre of in-stream pools;								###			###	###
Along the edges of in-stream pools;	###				#						###	###
In/around leafy snags;	###				###						###	###
In/around small woody snags;	###				###						###	###
In/around large woody snags;	###				###			###			###	###

Estuary and transition zone

In mangrove forest;	###	###			###					###		
Along edges of mangrove forests;	###	###	###	##	###	###	###	###	###	###		
In/around mangrove forest drainage channels;	###	###			###	###	###	###	###	###		
In/around locations where wetlands drain into the estuary;	###	###			###	###	##	###	###	###		
Around creek junctions;	###				##	###	###	###	###	###		
In seagrass beds;	###			###					###	###		
Along edges of seagrass beds;	###			###		###		###		###		

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
Over seagrass beds;				###					###	###		
Around mussel, clam or oyster beds;	###	###	##		###	###		###	###	###		
Around areas of rubble;	###	###	###		###	###		###	###	###		
Around areas of large rocks;	###	###	###		###	###		###	###	###		
Around areas of boulders;	###	###	###		###	###		###	###	###		
Around underwater cliffs;	###	###	###		###					###		
On subtidal open bottom areas;		##				###		###	###	###		
In/around leafy snags;	###	###			###					###		
In/around small woody snags;	###	###	###		###			###		###		
In/around large woody snags;	###	###	###		###			###		###		
On open flat areas of sand banks;				###		###	###	###	###	###		
In channels on sand banks;	###	###		###		###	###	###	###	###		
Around sand bank edges;	###	###		###		###	###	###	###	###		

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
Around fronts (e.g. turbidity plumes, areas where different water bodies meet [often identifiable by a change in water colour or temperature, or accumulation of floating debris]);	###					###	###	###				
In open water with no discernible structure;						###	##	###				
Coastal zone, reef and offshore												
In seagrass beds;				###						###		
Along edges of seagrass beds;				###	###	###		###	###	###		
Around mussel, clam or oyster beds;		###			###	###		###	###	###		
Around other biogenic structure (whip coral, sea fans, sponges etc.);		###								###		
Around areas of rubble;	###	###	###						###	###		
Around areas of large rocks;	###	###	###		###	###		###	###	###		
Around areas of boulders;	###	###	###		###	###		###	###	###		
Around underwater cliffs;		###	###		###			###		###		

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
In caves;		###	###		###							
Along lower edge of rocky reefs;		###	###		###	###		###	###	###		
On subtidal open bottom areas;						###	###	###	###	###		
On open flat areas of sand banks;				###		###	###	###	###	###		
In channels on sand banks;	###			###		###	###	###	###	###		
Around sand bank edges;				###		###	###	###	###	###		
On coral reef crests;		###				###		###				
In coral gutters;		###	###					###				
Around coral bommies;		###	###			###		###				
On coral reef slopes;		###	###			###		###				
Along lower edge of coral reef slopes;		###	###		###							
Around fronts (e.g. turbidity plumes, areas where water bodies meet [often identifiable by a change in water colour/temperature or accumulation of floating debris]);						###		###				

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
Associated with floating objects;												
In open water with now discernible structure;						# # #		# # #				
depth range	0-6m	0-30m	4-30m	0-4m	0-20m	0-15m	0-6m	0-30m	0-20m	0-10m	0-2m	0-2m

Appendix 3 Table 1: Summary of responses from face-to-face (41 responses) and on-line (12 responses) surveys of expert anglers (either commercial sportfishing operators or recognised local experts) about fish habitat use over 3 scales (Process zone; Macro-habitat; Micro-habitat). Responses are recorded only as relative rankings - these are qualitative responses so the meaning of the proportion of responses for any category is ambiguous. For instance, single response could indicate a key habitat relationship that is unknown to other anglers, while a habitat identified by most could simply relate to a commonly held, but erroneous, belief. Categories; (some) # 0-0.4; (many) # # >0.4-0.8; (most) # # #>0.8-1.0

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
total responses	34	30	21	11	38	30	15	33	16	27	23	21
1: PROCESS ZONE												
Freshwater												
Upland freshwater streams;												# # #
Lowland freshwater streams;					# # #			# # #	# # #			# # #
Floodplain freshwater wetlands;	# # #				# # #				# # #			
Estuary and transition zone												
Coastal brackish or tidal wetlands;	# # #	# # #			# # #					# # #		
Estuary transitional zone (the upper part of the estuary that can become low salinity during wet-season flooding;	# # #	# # #			# # #	# # #		# # #		# # #		

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
The main part of the estuary (mangrove line channels);	###	###	###	###	###	###	###	###	###	###		
Estuary mouth;	###	###	###	###	###	###	###	###	###	###		
Coastal zone												
Beaches;	###			###		###	###	###		###		
Headlands;	###	###	###		###	###	##	###	###	###		
Coastal reefs;		###	###	###	###	###		###	###			
Coastal zone open waters (within about 500m of coast but not beaches, sandbanks, headlands or reefs);												
Reef and offshore												
Coral reefs;		###	###		###	###		###				
Islands;		###	###		###	###		###				
Inter-reefal areas (outside the coastal zone and deep water among reefs);			###					###				
Offshore waters;						###		###				

2: Macro-habitat

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
Freshwater												
Rapids;											###	###
Vegetated stream banks;	###				###						###	###
Unvegetated stream banks;											###	###
Stream channels;											###	###
In-stream pools;					###			###			###	###
Lakes, lagoons, billabongs, off-stream pools;	###				###						###	
Near coffee rock;	###				###						###	###
Estuary and transition zone												
Vegetated stream banks;	###	###			###		###			###		
Unvegetated stream banks;							###			###		
Lakes, lagoons, billabongs, off-stream pools;	###				###					###		
Mangrove forests;	###	###			###		###			###		
Intertidal mudflat;	###			###		###	###	###	###	###		
Intertidal sand flat;	###			###		###	###	###	###	###		

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
Intertidal rubble;	###	###	#	###	###				###	###		
Intertidal rocky;	###	###	###	###	###				###	###		
Subtidal rubble;	###	###	##		##				###	###		
Subtidal rocky;	###	###	###		###				###	###		
Steep-sided channel banks;	###	###	#		##	###	###	###	###	###		
Seagrass beds;	###	###	#	###	##	###		###	###	###		
Deep rocky (i.e. completely subtidal);	###	###	###		##			###	###	###		
Shallow rocky (i.e. partly or mainly intertidal);	###	###	#	###	###				###	###		
Deep (subtidal) unvegetated open bottom;			###			###	###	###	###	###		
Water column (i.e. associated with surface or sub-surface waters but not necessarily associated with a particular bottom type);						###		###				
Near coffee rock;	###	###	#		###			###		###		

Coastal zone, reef and offshore

Mangrove forest	###	###			###		###	###		###		
Seagrass beds;								###		###		

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
Intertidal sand flats;				# # #		# # #	# # #	# # #	# # #	# # #		
Intertidal rubble;	# # #	# # #	#	# # #	# # #	# # #	# # #	# # #	# # #	# # #		
Intertidal rocky;	# # #	# # #	# #	# # #	# # #				# # #	# # #		
Subtidal sand flats;				# # #		# # #	# # #	# # #	# # #	# # #		
Subtidal rubble;	# # #	# # #	# #		# # #	# # #		# # #	# # #	# # #		
Shallow subtidal rocky;	# # #	# # #	#	# # #	# # #	# # #		# # #	# # #	# # #		
Deep rocky (i.e. completely subtidal);			# # #						# # #			
Deep unvegetated open bottoms;						# # #	#	# # #	# # #			
Coral reef crest;								# # #				
Back reef;		# # #										
Reef lagoon;		# # #						# # #				
Coral reef slope;		# # #	# #									
Deep-water coral reef;		# # #	# # #					# # #				
Water column (i.e. associated with surface or sub-surface waters but not associated with a particular bottom type);						# # #		# # #				
Near coffee rock;	# # #	# # #	# # #		# # #					# # #		

3. Meso-habitat

Freshwater

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
In vegetation;	# # #				# # #						# # #	# # #
Alongside vegetation;					# # #						# # #	# # #
Among rocks in rapids;											# # #	# # #
In pools in rapids;	# # #										# # #	# # #
In the centre of in-stream pools;								# # #			# # #	# # #
Along the edges of in-stream pools;	# # #				#						# # #	# # #
In/around leafy snags;	# # #				# # #						# # #	# # #
In/around small woody snags;	# # #				# # #						# # #	# # #
In/around large woody snags;	# # #				# # #			# # #			# # #	# # #
Estuary and transition zone												
In mangrove forest;	# # #	# # #			# # #					# # #		
Along edges of mangrove forests;	# # #	# # #	# # #	# #	# # #	# # #	# # #	# # #	# # #	# # #		
In/around mangrove forest drainage channels;	# # #	# # #			# # #	# # #	# # #	# # #	# # #	# # #		

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
In/around locations where wetlands drain into the estuary;	###	###			###	###	##	###	###	###		
Around creek junctions;	###				##	###	###	###	###	###		
In seagrass beds;	###			###					###	###		
Along edges of seagrass beds;	###			###		###		###		###		
Over seagrass beds;				###					###	###		
Around mussel, clam or oyster beds;	###	###	##		###	###		###	###	###		
Around areas of rubble;	###	###	###		###	###		###	###	###		
Around areas of large rocks;	###	###	###		###	###		###	###	###		
Around areas of boulders;	###	###	###		###	###		###	###	###		
Around underwater cliffs;	###	###	###		###					###		
On subtidal open bottom areas;		##				###		###	###	###		
In/around leafy snags;	###	###			###					###		
In/around small woody snags;	###	###	###		###			###		###		
In/around large woody snags;	###	###	###		###			###		###		
On open flat areas of sand banks;				###		###	###	###	###	###		

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
In channels on sand banks;	###	###		###		###	###	###	###	###		
Around sand bank edges;	###	###		###		###	###	###	###	###		
Around fronts (e.g. turbidity plumes, areas where different water bodies meet [often identifiable by a change in water colour or temperature, or accumulation of floating debris]);	###					###	###	###				
In open water with no discernible structure;						###	##	###				

Coastal zone, reef and offshore

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
In seagrass beds;				###						###		
Along edges of seagrass beds;				###	###	###		###	###	###		
Around mussel, clam or oyster beds;		###			###	###		###	###	###		
Around other biogenic structure (whip coral, sea fans, sponges etc.);		###								###		
Around areas of rubble;	###	###	###						###	###		
Around areas of large rocks;	###	###	###		###	###		###	###	###		
Around areas of boulders;	###	###	###		###	###		###	###	###		

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
Around underwater cliffs;		###	###		###			###		###		
In caves;		###	###		###							
Along lower edge of rocky reefs;		###	###		###	###		###	###	###		
On subtidal open bottom areas;						###	###	###	###	###		
On open flat areas of sand banks;				###		###	###	###	###	###		
In channels on sand banks;	###			###		###	###	###	###	###		
Around sand bank edges;				###		###	###	###	###	###		
On coral reef crests;		###				###		###				
In coral gutters;		###	###					###				
Around coral bommies;		###	###			###		###				
On coral reef slopes;		###	###			###		###				
Along lower edge of coral reef slopes;		###	###		###							
Around fronts (e.g. turbidity plumes, areas where water bodies meet [often identifiable by a change in water colour/temperature or accumulation of floating debris]);						###		###				

	Barramundi (*Lates calcarifer*)	Estuary cod (*Epinephelus* spp.)	fingermark (*Lutjanus johnii*)	Golden trevally (*Gnathanodon speciosus*)	Mangrove jack (*Lutjanus argentimaculatus*)	Queenfish (*Scomberoides commersonnianus*)	threadfin salmon (Polynemidae)	giant trevally (*Caranx ignobilis*)	Javelin fish (*Pomadasys* spp.)	Pikey bream (*Acanthopagrus pacificus*)	Sooty grunter(*Hephaestus fuliginosus*)	Jungle perch (*Kuhlia rupestris*)
Associated with floating objects;												
In open water with now discernible structure;						# # #		# # #				
depth range	0-6m	0-30m	4-30m	0-4m	0-20m	0-15m	0-6m	0-30m	0-20m	0-10m	0-2m	0-2m

Appendix 4. Key resources provided by critical habitats over life histories

Kátya Abrantes and Marcus Sheaves

Executive Summary

Coastal ecosystems are often highly productive and provide important habitats to many important fisheries species that use these areas as nursery, feeding and/or reproduction grounds. The diversity of coastlines results in differences in types of provisioning and function, and in community structure and trophic organisation. Since almost all coastal fishery species require particular components of the seascapes during specific stages of their life-cycles, it is important to understand the way fish use different habitats throughout ontogeny. Access to rich feeding environments is a key contributor to habitat value, and so knowledge on food webs and feeding relationships, and how these vary over space and time, is central to understanding the importance of the different coastal environments. However, the functional roles of the different habitats in supporting fishery species are still not well understood for most regions. In this study, we review and discuss the available literature to identify key knowledge gaps in the understanding of habitat- and context- specific food webs and trophic interactions supporting Australian coastal fisheries species. Given the ever increasing transformation of coastal landscapes by either direct human action or by sea level rise and changing climate, these knowledge gaps need to be urgently addressed for appropriate management and mitigation of various impacts. We conclude that understanding the key prey resources and food web linkages that support all life-stages of fishery species is a high priority for their sustainable management, especially for species that participate in food webs that transcend the individual habitat units that are the common focus of management.

1. Introduction

1.1. Background

Coastal ecosystems such support a diversity of fisheries by providing crucial spawning (e.g. Gray & Miskiewicz 2000), feeding (e.g. Begg & Hopper 1997) and nursery grounds (e.g. Beck et al. 2001, Sheaves et al. 2015) to a large proportion of fishery species. However, they are also among the most threatened systems (Kennish et al. 2011). Because access to rich feeding environments is a key contributor to habitat value, knowledge on food webs and feeding relationships, and how these vary over space and time, is central to understanding the importance of the different coastal habitats. Although understanding the food webs that support fishery species throughout all stages of their lives is critical for effective management (Sheaves et al. 2015), the functional roles of the different habitats in supporting fishery species are still not well understood for most regions. The loss or disruption of key productivity sources, densities and/or composition of predators or prey, or food web connectivity can lead to population collapses or prevent recovery from population declines (Swain & Sinclair 2000, Link 2002) and have cascading effects on ecosystems (Pinnegar & Polunin 2000, Altieri et al. 2012). As a result, even when fisheries themselves and the key habitats supporting them are well managed, fish stocks may decline if important trophic links are altered (Boström et al. 2011, Fogarty 2013), illustrating the importance of accurate food web information for fisheries sustainability.

1.2. Objectives

The aim of this study is to review our understanding of food webs that support Australian fisheries species in coastal systems. We firstly focus on some of the most commonly managed habitat units: mangroves, saltmarshes, seagrass beds and reefs (Beck et al. 2001). We then investigate how food webs connect among and across these habitat units and through time rather than being static relationships specific to particular units of habitat. We end by identifying the most important knowledge gaps and proposing the most productive avenues for future research to support and advance the management of fishery species and their supporting habitats.

2. Food webs that support Australian fisheries species

The diversity of coastal ecosystems and seascape mosaics found around Australia results from differences in climate, geomorphology, and the range, distribution, and availability of habitats and of primary producers within habitats. This in turn leads to large differences in community structure and trophic organisation. For example, the estuaries of tropical eastern Australia comprise a range of interconnected intertidal habitats, including seagrass beds, mangrove forests, saltmarsh and salt pans, intertidal flats, as well as littoral floodplain forests, coastal lagoons and swamps that are seasonally connected by flooding to estuaries. This mosaic of coastal habitats provides a diversity of feeding opportunities for species with diverse feeding strategies, from species such as flathead that spend most of their lives in one habitat type to others such as barramundi which range widely, connecting food webs across the coastal seascape. In the high wave energy south west coast of Western Australia, coastal habitats are characterised by extensive subtidal seagrass meadows and limestone reefs dominated by macroalgae. Exposed sandy beaches with abundant wrack deposits are separated from the terrestrial environment and coastal wetlands by sand dunes which, coupled with the restricted seasonal rainfall, limits connectivity between the marine environment, other coastal wetlands and the terrestrial environment. In the end of this spectrum, in the high limestone cliffs that dominate the high energy coastline bordering the arid Nullarbor Plain on the Great Australian Bight (southern Australia), there are almost no estuaries or coastal wetlands for thousands of kilometers. These contrasting environments generate very different contexts for the development of food webs supporting fisheries species and, therefore, for different habitat functions and values.

2.1. Mangroves

Mangrove forests are widely considered critical in supporting fisheries production (Manson et al. 2005b, Meynecke et al. 2007). In Australia, mangroves occur mostly around the northern and eastern coasts (Fig. A4-1a), in low wave energy environments. Juvenile nekton of many species primarily occupy mangroves and associated subtidal channels, reflecting the global importance of mangrove ecosystems as key nursery grounds for fish and invertebrates such as banana prawns and mud crabs (Nagelkerken et al. 2008). Despite their importance, most studies on mangrove habitats are limited to comparisons of animal communities between these habitats and adjacent seagrass beds or unvegetated habitats (e.g. Robertson & Duke 1987, Laegdsgaard & Johnson 1995), and there is still much debate on the energetic links between mangrove production and aquatic consumers (Layman 2007, Bouillon et al. 2008, Igulu et al. 2013).

The mangrove forests of northern Australia are highly productive (Clough 1998) and contribute to a large proportion of the available organic carbon in estuarine waters (Alongi et al. 1998). However, despite the large expanses of mangrove forests and high availability of mangrove-derived carbon, its importance as a direct source of nutrition for fishery species is limited, with food webs in mangrove areas mostly based on a combination of aquatic producers such as phytoplankton, seagrass and microphytobenthos (Loneragan et al. 1997, Abrantes & Sheaves 2008, 2009b, Oakes et al. 2010). A notable exception are groupers (*Epinephelus* spp.), snappers (*Lutjanus* spp.) and bream (*Acanthopagrus* spp.) which in northern Queensland feed extensively on mangrove-feeding sesarmid crabs, as part of a very short food chain from mangroves to large predatory fish (Sheaves & Molony 2000, Sheaves et al. 2014).

In temperate eastern Australia (Victoria, South Australia, New South Wales), mangroves are confined to sheltered shores such as estuaries, embayments and inlets, while in Western Australia these are mostly distributed through the northern and western shores, and are abundant only in the northern regions of the Kimberley and Pilbara. Studies in these areas also indicate that mangroves are of little importance to consumer nutrition, and that aquatic producers are the most important contributors (Hadwen et al. 2007, Heithaus et al. 2011). Nevertheless, even where mangrove production plays only a minor role in supporting fishery species, mangrove forests provide rich foraging habitats with prey supported by a variety of sources (Igulu et al. 2013), and fishery landings are higher in areas adjacent to mangrove forests (Manson et al. 2005a, Manson et al. 2005b, Meynecke et al. 2007).

While the detailed mechanisms are yet to be resolved, recent work indicate that where together with coral reefs and seagrass beds, mangroves are an integral component of tropical coastal seascapes that support abundant and diverse communities, including fishery species (Nagelkerken et al. 2008, Olds et al. 2012).

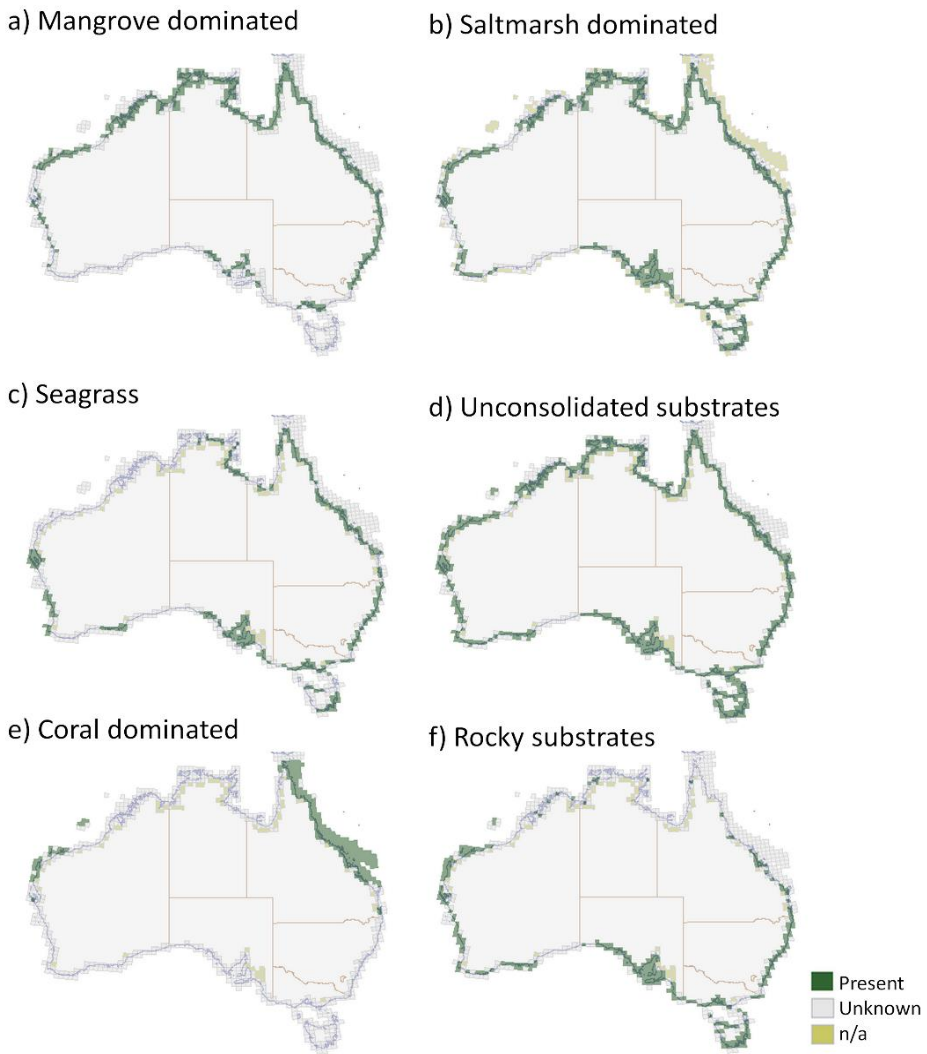

Figure A4-1. The distribution of the different coastal habitats along the Australian coastline. Squares represent 50 km grids cells. Source: OzCoasts (2009)

2.2. Saltmarshes

As mangroves, saltmarshes (Fig. A4-1b) are used by a range of fisheries fish and invertebrate species. In tropical regions, saltmarshes generally occur landward of mangrove forests, while in southern temperate regions vast expanses of saltmarsh occur in place of mangroves directly adjacent to subtidal waterways. Although saltmarshes are more extensive in the northern half of Australia (Bucher & Saenger 1991), most saltmarsh research has been conducted in temperate regions (e.g. Connolly et al. 1997, Thomas & Connolly 2001, Crinall & Hindell 2004, Bloomfield & Gillanders 2005, Saintilan et al. 2007). Work in the tropics has concentrated on permanent (Sheaves et al. 2007)(Sheaves et al. 2007, Sheaves and Johnston 2008 (Sheaves

& Johnston 2008, Davis et al. 2012) and temporary (Russell & Garrett 1983) saltmarsh pools. Juveniles of a number of species use both types of pools which, together with freshwater wetlands, are considered important juvenile habitats for species such as the iconic barramundi (Rusell & Garrett 1983, Sheaves et al. 2007).

Most saltmarsh habitats in northern Australia occur high in the intertidal and are only submerged during the highest spring tides and for relatively short periods of time (Connolly 2009, Davis et al. 2012). Nevertheless, a number of studies reported the consumption of saltmarsh invertebrates by fish (e.g. Guest & Connolly 2004, Guest & Connolly 2006, Abrantes & Sheaves 2008, 2009b), meaning that despite the low frequency of inundation, saltmarsh carbon can be important for fishery species. Also, juveniles of fish such as yellowfin bream (*Acathopagrus australis*) feed substantially on terrestrial invertebrates such as flies, spiders, grasshoppers, dragonflies and even skink lizards in saltmarsh habitats (Morton et al. 1987), further increasing the importance of saltmarsh habitats for these fisheries.

Overall, the few studies that provide quantitative information on the incorporation of either saltmarsh or mangrove material by Australian fishery species indicate that these producers have limited importance for consumers in tropical (Abrantes & Sheaves 2008, 2009b), subtropical (Melville & Connolly 2003, Connolly et al. 2006), and temperate regions (Svensson et al. 2007), and that food webs supporting adjacent fisheries rely mostly on aquatic sources such as plankton, microphytobenthos and seagrass. However, because the importance of saltmarsh/mangroves to fish and invertebrates depends on the assemblage and relative availability of different habitats/sources (Polis et al. 1997, Svensson et al. 2007), the different producers are likely to have different patterns of importance, depending on the environmental conditions of each area. For example, riparian vegetation is likely to have greater importance for consumers in intermittently open estuaries due to increased water residency time compared to open estuaries (Hadwen et al. 2007), while the importance of aquatic and terrestrial production is likely to alternate in areas with extreme hydrological seasonality (Abrantes & Sheaves 2010). Finally, while mangrove and marsh production itself may be of limited importance for fishery species, these wetland plants are foundation species that support a diversity of other production sources and rich prey that may be critical for fishery species (Igulu et al. 2013).

2.3. Seagrass meadows

Australia's seagrass habitats support high diversities and abundances of invertebrates and fish, including many fishery species (Edgar & Shaw 1995a, Haywood 1995, Jenkins et al. 1997)[. Major seagrass areas occur around Australia, especially along the low wave energy northern coastlines (Fig. A4-1c). In the high energy southern coast, seagrass distribution is patchy and generally restricted to estuaries, protected bays and coastal lagoons. As with mangroves and saltmarshes, seagrass habitats have long been recognised as important nursery grounds (Heck et al. 2003).

In northern Australia, important fisheries species such as tiger (*Penaeus esculentus* and *P. semisulcatus*) and endeavour (*Metapenaeus endeavouri*) prawns use on seagrass beds as nurseries (Haywood 1995). However, juvenile penaeids rely on different production sources depending on their position in the seascape. For example, in the Embley River, Cape York Peninsula, animals in seagrass habitats depend mostly on seagrass and their epiphytes, while those in macroalgae beds in mangrove creeks depend mostly on macroalgae and seston (Loneragan et al. 1997). Since penaeid prawns are a major prey for many fishery species including barramundi, bream and snappers (Robertson 1988, Salini et al. 1990), the nutrient flow from seagrass to these fish via penaeids must be significant. However, because penaeid prawns undergo important ontogenetic variations in diet (Abrantes & Sheaves 2009b), and can rely on different sources depending on habitat (Loneragan et al. 1997, Abrantes & Sheaves 2009b), the sources of nutrition for juveniles and their predators is likely to be quite variable among regions.

Seagrass meadows are also important nurseries for other commercially important crustaceans such as blue swimmer crabs (*Portunus pelagicus*) and rock lobsters (*Panulirus cygnus*) in south western Australia. Juveniles of these species forage on invertebrates and plant material in seagrass meadows, but stable isotope studies have shown that macroalgae, rather than seagrass, is their main source of nutrition (Joll & Phillips 1984, de Lestang et al. 2000, MacArthur et al. 2011). However, different sized juveniles forage in different habitats, and as for penaeid prawns there can be variations in diet between sites and seasons (Joll & Phillips 1984). So, while the importance of seagrass production for these species will vary depending on the seascape context, seagrass could be an important production source during particular life-history stages.

Besides garfish (*Hyporamphus* spp.) (Edgar & Shaw 1995b, Carseldine & Tibbetts 2005, Tibbetts & Carseldine 2005), no other Australian commercial finfish species is known to feed substantially on seagrass. The primarily herbivorous luderick (*Girella tricuspidata*) also occur in seagrass habitats (Kingsford 2002) but feed mostly on macroalgae, with seagrass making only a small contribution to their diet (Clements & Choat 1997, Raubenheimer et al. 2005). Nevertheless, seagrass is directly or indirectly (through the detrital pathway) consumed by a range of macroinvertebrates, which are then prey for carnivorous fish such as flathead and whiting (*Sillago* spp. and *Sillaginodes punctatus*), and therefore contributes to important fishery food webs (Robertson 1984, Hindell 2006). Indeed, stable isotope and fatty acid studies indicate that seagrass carbon is ultimately important for a range of fishery species including flathead in Victoria (Klumpp & Nichols 1983, Nichols et al. 1986), whiting in South Australia (Connolly et al. 2005), tarwhine (*Rhabdosargus sarba*) and whiting in Western Australia (Belicka et al. 2012), and queenfish (*Scomberoides* spp.) and trevallies (e.g. *Caranx* spp., *Carangoides* spp.) in Queensland (Abrantes & Sheaves 2009a).

Seagrass meadows also support high biomass of invertebrates that feed on seagrass epiphytes (Valentine & Duffy 2006). Some detailed work in Victoria showed that these invertebrates form important prey for a diversity of fish species (Edgar & Shaw 1995b) and that these seagrass areas support much higher fish densities than adjacent unvegetated habitats (Edgar & Shaw 1995a), therefore indirectly supporting fish production (Edgar & Shaw 1995c).

While these studies noted relatively low abundances of fisheries species in the studied habitats, seagrass support of fisheries is still likely to be significant as the abundant fish and invertebrates are likely important prey for fisheries species. Furthermore, detritus from seagrass meadows can be an important source of production supporting fishery species in adjacent habitats (Connolly et al. 2005, Heck et al. 2008).

Although similarly detailed understanding is lacking in many other regions around Australia, the trophic contribution of seagrass to fisheries is likely to vary between regions depending on the availability of alternate producers in the seascape, the extent and productivity of seagrass meadows, and the nature of consumer assemblages. For example, in Torres Strait (Queensland) and Shark Bay (Western Australia), where some of the largest seagrass areas in Australia occur, shallow and relatively clear waters mean that food webs rely mostly on benthic producers such as benthic microalgae and seagrass (Fry et al. 1983, Belicka et al. 2012, Speed et al. 2012). In systems like the relatively turbid Hinchinbrook Channel, however, seagrass productivity is limited by turbidity, so its relative importance is reduced and consumers rely on a combination of sources including seagrass, plankton, microphytobenthos, and mangroves (Abrantes & Sheaves 2009a).

Recent reviews have highlighted that despite considerable research effort, gaps in our knowledge of seagrass food webs limit our understanding of their support of fishery species, and of the overall structure and function of seagrass ecosystems. As for mangroves and saltmarshes, although seagrass production may be significant for only a limited range of fishery species, seagrass ecosystems appear to form critical components of coastal seascapes that support a diversity of fishery species.

2.4. Coastal rocky and coral reefs

Coastal reefs, including rocky reefs and fringing coral reefs, provide important habitat for many fisheries species. **Fringing coral reefs** occur in tropical shallow waters, where they can extend as reef flats to the shore, and also around continental islands. These structures occur mainly along Western Australia, particularly in the Kimberly region and Ningaloo coast, in the Northern Territory and also in Queensland, especially along the eastern Cape York Peninsula (Short 2006) (Fig. A4-1e). Ningaloo Reef, in Western Australia, is Australia's largest fringing reef, reaching up to 1400 m in width, and stretching for 260 km along the coast (Short 2006).

A range of primary producers is available in fringing coral reefs, including micro- and macro-algae, and seagrass, supporting important fisheries such as rock lobsters (*P. cygnus* and *P. ornatus*), groupers and trout (Serranidae, particularly the coral trout *Plectropomus* leopardus), emperors (Lethrinidae), snappers (Lutjanidae) and sweetlips (Haemulidae). Despite the plethora of coral reef ecology studies in Australia and overseas, there have been no detailed and quantified food web studies on fringing reefs. As in other coastal systems, there are likely several trophic pathways in coral reef systems, based on different producers (planktonic and benthic microalgae, macroalgae and seagrass). For example, many species feed directly on reef macroalgae, including sea urchins and rabbitfish (*Siganus* spp.), sea chubs (*Kyphosus* spp.) and unicornfishes (*Naso* spp.) (Clements & Choat 1997, Hoey 2010, Michael et al. 2013), and these support some fisheries and are also important food for predatory fish such as emperors, groupers and sharks (Westera et al. 2003, Johansson et al. 2013), transporting this macroalgal carbon up the food chain. On the other hand, small planktivores (e.g. clupeids) are also abundant in the waters around reefs, and primarily form the base of the diet of pelagic carnivores such as scombrids, sphyraenids and carangids, in another important pathway.

In a recent study in Ningaloo Reef, Wyatt et al. (2012) found that detritivorous and corallivorous fish species rely on benthic reef productivity throughout the reef width, while carnivores, herbivores and planktivores rely increasingly on oceanic productivity with distance from the shore. While a number of stomach content studies on coral reef fishery species are available (e.g. Connell 1998, St John 1999), the multiplicity of primary producers in close proximity makes it difficult to quantify the contributions of different sources for consumers, even if based on techniques such as stable isotope and fatty acid analysis (e.g. Wyatt et al. 2012). As a consequence, the relative balance of the various reef-based and pelagic production sources in supporting coral reef fishery species remains largely unknown.

Rocky reefs occur in less than 20% of Australia's coastline (Fairweather & Quinn 1995; Fig. A4-1f), and are particularly abundant in temperate southern Australia. These habitats provide habitat for commercially and recreationally important invertebrate species such as rock lobster (*Jasus* spp.), and for fish such as luderick (*Girella* spp.), bream (*Acanthopagrus* spp.), tailor (*Pomatomus saltator*), morwong (*Cheilodactylus* spp.) and wrasses (*Notolabrus* spp.).

The main sources of nutrition for rocky reef consumers will likely depend on factors such as hydrology, geomorphology and seascape characteristics. For example, in intertidal and subtidal rock flats, surfaces are often covered in algae, including turf and coralline algae, that are food for grazing invertebrates (e.g. gastropods, crabs) and fish (e.g. luderick, sea chubs, leatherjackets) (Jones & Andrew 1990, Guest et al. 2008). Sessile filter-feeders (e.g. sponges, ascidians, bryozoans, bivalves) are also common in these habitats, and feed mostly on plankton (Young 1990), providing a pathway to incorporate plankton-based production into fisheries food webs. Other areas such as the western coast of south Western Australia, which is characterized by a series of limestone ridges that run parallel to the coastline, are dominated by macroalgae interspersed with unvegetated sand and seagrass meadows, also allowing different trophic pathways to co-occur. However, in regions such as in the Nullarbor Cliffs in the Great Australian Bight, Port Campbell (Victoria), around Sydney (New South Wales) and in southern Tasmania, vertical cliffs and high wave energy waters limit the areas suitable for attachment of sessile organisms, thus limiting the range of available producers and the number of possible trophic pathways through to fisheries species. There, plankton is likely to have a greater importance than in shallow, low energy coastlines. However, in those regions, subtidal rocky reefs often support dense kelp forests that support important species such as rock lobsters, abalone, and snapper. Little is known about the trophic importance of the different rocky reef habitats.

2.5. Other habitats

Although mangroves, saltmarshes, seagrass meadows and reefs generally attract more attention and are most often considered in management (Beck et al. 2001, Harborne 2009), other habitats such as sand and mudflats and coastal pelagic habitats such as deeper areas of bays and off coastal headlands can also be important for a range of fishery species.

Sand- and mudflat habitats occupy a large proportion of Australia's coastal zone (Short 2006) (Fig. A4-1d), and include intertidal habitats like beaches, sand and mud banks in estuaries and coastal lagoons, as well as subtidal areas of consolidated and mobile sands and muds. In general, these habitats are characterised by limited macroscopic vegetation or other complex structure. The physical properties (e.g. wave energy, slope, grain size,) and seascape settings (assemblage of habitats available) play a major role in determining the importance of local vs. imported production in these environments (Degré et al. 2006, Bergamino et al. 2011). Large intertidal and/or subtidal sand and mudflats often occur adjacent to estuarine and lagoonal habitats such as mangroves, saltmarshes, seagrass meadows and reefs. Fish and invertebrates can move between habitats and this connectivity between habitats is important to maintain the ecological value of these systems (Nagelkerken 2009, Sheaves 2009). In some of these areas, high microphytobenthos productivity (MacIntyre et al. 1996) can support local food webs (e.g. Middelburg et al. 2000, Galván et al. 2008, Shahraki et al. 2014) and even subsidize food webs in neighboring habitats through dispersal of suspended benthic microalgae produced on the flats (e.g. Yoshino et al. 2012). In other regions, however, fishery species in mudflats rely mostly on carbon imported from adjacent habitats such as seagrass beds (Connolly et al. 2005, Melville & Connolly 2005). The presence of a range of habitats dominated by different primary producers in close proximity and the movement of carbon through the seascape through water and animal movement means that food webs in these flats are likely to rely on a range of sources, and therefore that the different habitats will have different values for the different fisheries species. The relative importance of each source will depend on the productivity of the different primary producers in the assemblage of habitats that constitute the coastal mosaic, as well as on the level of connectivity among habitats.

In beaches not associated to estuaries or lagoons, however, intertidal and subtidal flats are generally only neighbored by the terrestrial environment and open water habitats. Sandy beaches are often highly dynamic and provide little structural complexity (McLachlan & Hesp 1984, Robertson & Lenanton 1984), and so are unsuitable for many species. However, they can provide alternative habitats for some species generally associated with estuaries such as whiting and bream (Lenanton 1982, Robertson & Lenanton 1984, Lenanton & Potter 1987, Ayvazian & Hyndes 1995). Although high energy beaches have low *in situ* primary production (McLachlan & Brown 2006), in some areas high concentrations of diatoms accumulate in the surf zones (Campbell 1996) and can fuel local food webs, but to date no research has been done on the importance of these producers for fishery species occupying beaches in Australia. However, in most cases, food webs depend mostly on allochthonous inputs from offshore, from land and/or from other coastal habitats (McLachlan & Brown 2006). Detached macrophytes are often transported from distant areas and accumulate in surf zones, forming beach wrack, which is particularly abundant along the wave-dominated coasts of temperate Australia (e.g.

Duong & Fairweather 2011). Much work on the importance of this wrack for aquatic consumers has been done in Australia (e.g. Lenanton et al. 1982, Crawley et al. 2006, Crawley et al. 2009). Macrophyte subsidies increase productivity in these otherwise nutrient poor and unproductive environments (Kirkman & Kendrick 1997), providing important food and habitat for macroinvertebrates (Ince et al. 2007) and fish (Lenanton et al. 1982, Robertson & Lenanton 1984, Crawley et al. 2006). Bacteria that break down beach wrack are responsible for most secondary production in these areas (McLachlan 1985). Benthic macrofauna, dominated by large populations of amphipods, with isopods and insects also present, is consistently more abundant on high-wrack beaches (McLachlan 1985, Ince et al. 2007). These invertebrates are in turn important prey for fish, including fishery species such as whiting, bream and Australian salmon (Lenanton et al. 1982, Robertson & Lenanton 1984, Crawley et al. 2006), forming short and simple food webs from macrophyte detritus through colonising microbes, to detritivorous invertebrates and fish. Because algae are generally more easily assimilated than seagrass (Klumpp 1989), the algal component of wrack is often preferred by detritivores (Crawley et al. 2009, Doropoulos et al. 2009). However, there are no quantitative estimates of the relative importance of the different wrack components and other sources such as marine plankton to fishery species that use these habitats. This importance is likely to vary both spatially and seasonally depending on factors such as wrack availability and species composition and abundance, as well as the assemblage of primary consumer invertebrates.

In coastal pelagic habitats such as deeper areas of large bays and off coastal headlands, mobile piscivores such as queenfish (*Scomberoides* spp.), mackerels (*Scomberomorus spp.*), trevallies (e.g. *Caranx* spp., *Carangoides* spp.), kingfish (*Seriola* spp.), Australian salmon (*Arripis* spp.) and sharks, especially Charcharinids, are some of the most important fisheries species. Some of these species, such as mackerels and Australian salmon, feed mostly on small pelagic prey such as clupeids and engraulids (Begg & Hopper 1997, Hughes et al. 2013), as part of strong plankton-based food webs. Others, such as queenfish, trevallies and sharks (Salini et al. 1994, Yick et al. 2012), feed on a range of pelagic and benthic fish and invertebrates. These deeper areas can also support high densities of important invertebrates such as penaeid prawns (Somers et al. 1987), cephalopods (Dunning et al. 1994) and scallops (Tracey & Lyle 2011). Depending on environmental factors such as depth, turbidity, substrate type and seascape characteristics, pelagic and benthic producers will have different contributions to food webs supporting these species in different regions.

2.6. Movement of carbon between habitats

In some cases, fisheries species that occur in one habitat can depend on energy produced in a different habitat. Indeed, animals in the different habitats often rely on various sources of nutrition, including local primary production (autochthonous sources) and material imported from adjacent habitats (allochthonous sources). The relative importance of these sources depends on the availability and assemblage of sources, and this partially depends on factors such as productivity and spatial distribution of habitats (Polis et al. 1997). Imported material can support food webs in both productive habitats such as inshore reefs and seagrass and algal beds, as well as in unproductive habitats such as sandy beaches (Polis et al. 1997, Heck et al. 2008). Several studies from around Australia have identified important exchanges of material between distant aquatic habitats, e.g. subsidies of detached macrophytes fuelling food webs in otherwise unproductive beaches (Lenanton et al. 1982, Robertson & Lenanton 1984), in adjacent seagrass beds and in less productive inshore reefs (Wernberg et al. 2006, Hyndes et al. 2012), and seagrass subsidies supporting food webs in adjacent mudflats (Connolly et al. 2005, Connolly et al. 2006). In Tasmania, seagrass detritus transported offshore during storms support larval stages of blue grenadier (*Macruronus novaezelandiae*) recruiting into coastal habitats (Thresher et al. 1992), forming an important energetic link between inshore and offshore habitats for a fishery species. Mass spawning of corals can also fuel pelagic and benthic food webs in adjacent habitats, as gametes and larvae are consumed by planktivorous organisms (Westneat & Resing 1988, Pratchett et al. 2001), and the deposition of gametes on the sediments (Wolanski et al. 1989) serves as food for benthic consumers, representing an important nutrient subsidy to these habitats ((Wild et al. 2008).

Coastal food webs can also receive important subsidies from the adjacent terrestrial environment (Connolly et al. 2009, Schlacher & Connolly 2009, Abrantes et al. 2013). For example, in North Queensland, terrestrial material transported from the Herbert River catchment contributes ~27% of the total organic carbon input for the Hinchinbrook Channel, more than aquatic sources, which together contribute only ~17% (Alongi et al. 1998, Alongi 2009). More directly, the transport of terrestrial invertebrates (ants, spiders, grasshoppers, etc.) into coastal habitats with the wind and flood waters can be important for the diets of carnivorous aquatic species (Nakano et al. 1999, Balcombe et al. 2005). Seasonal floods allow the connectivity between habitats such as main channels and floodplain wetlands, providing an opportunity for animals to move into different habitats (Sheaves & Johnston 2008, Abrantes & Sheaves 2010) and freshwater flows allow the delivery of nutrients, organic matter and sediments from river catchments to the coastal zone, stimulating phytoplankton growth, fuelling phytoplankton-based food webs (McComb & Humphries 1992, Connolly et al. 2009, Schlacher et al. 2009) and leading to increases in fishery production (Loneragan & Bunn 1999, Meynecke et al. 2006, Gillson 2011). Nevertheless, although several studies linked freshwater flows to fisheries production of several species (see reviews by Gillanders & Kingsford 2002, Robins et al. 2005, Meynecke et al. 2006, Gillson 2011), the mechanisms responsible for these relationships are not clarified for most species.

3. Knowledge gaps on the trophic support of coastal habitats to fishery species

Several knowledge gaps related to the trophic function and use of coastal habitats by fisheries species have been identified. Most importantly:

Basic dietary information is lacking for many species

Basic dietary information is missing for many species, and available studies rarely cover a size range that accounts for ontogenetic variations in diet or provide information on the habitat-specific diets of small (<5 cm) juveniles. This is important for management because of the need to protect critical resources to preserve fisheries species. For example, if shrimps found in seagrass beds are a major component of the diet of a fishery species, then seagrass beds, along with its shrimps, should be considered a high value habitat to be preserved.

Largely unknown range of habitats used by different life-cycle stages.

Basic information on habitat-related distribution of fishery species is lacking for most coastlines, but this information is fundamental for understanding the importance of the different components of the seascapes. Despite that the availability, quality and spatial distribution of habitats used at the different life stages are the primary determinants of a system's contribution to fisheries (Sheaves et al. 2015), even for the most well studied regions, basic information on habitat use, either for food, shelter, or reproduction, is still lacking for most species, resulting in an incomplete understanding of habitat needs and major gaps in knowledge about key food resources used by those life stages.

Geographic patchiness of available data.

Habitat research is incomplete and irregularly distributed around Australia. Since habitat use patterns can vary greatly depending on site-specific seascape characteristics, generalisations and extrapolations need to be done carefully.

Importance of different producers to fishery species.

Since much of the value of habitats is derived from their ability to provide food, precise understanding of both the main habitats (e.g. seagrass meadows) and specific primary producers within each habitat (e.g. seagrass epiphytes) supporting the different life-stages of the different species is paramount. For example, when a species relies mostly on material transported from an adjacent habitat for nutrition, it is important to also preserve that donor habitat even if that particular species does not occur in it.

Deficient understanding of the required physical connectivities between habitats

Most coastal fishery species require the access to a range of habitats to complete their life-cycle, and the required assemblage of habitats can vary between life-cycle stages. It is thus important to have a good understanding of the required physical connectivity between habitats, at appropriate spatial and temporal scales, but this aspect is often not considered. This information is crucial for fisheries management as for example it will allow identifying the habitats and physical connectivities that need to be preserved to maintain recruitment and survival of the different live stages of fishery species.

Deficient understanding of the energetic connectivities between habitats and their importance for fishery food webs

Throughout the world, degradation of coastal habitats and their connectivities is ever increasing, e.g. with the construction of barriers that prevent salt intrusion or increase the area of usable land, roads that cut off wetlands from their estuaries, or dams that prevent movement of carbon and animals between freshwater and estuarine reaches. Despite the recognised importance of energetic connectivity and subsidies for several systems, few studies attempted to identify and quantify these linkages in food webs supporting fishery species. This information is important to determine the habitats involved in nutrition provision and has therefore management implications. For example, if inputs or organic matter from terrestrial catchments are important for a coastal fishery species, then modification or loss of connectivity may have negative impacts on the sustainability of the fishery.

4. Conclusion

Although coastal habitats are important to many fish and invertebrates, the diversity of coastlines means that there are substantial differences in the way this importance is manifested, including in types and degrees of provisioning and function throughout the different species' ontogeny. Understanding the food resources and trophic linkages that support all life-stages of fishery species in the different habitats is critical for their sustainable management, especially for species that participate in food webs that span several habitat units commonly considered in management. This means that information on the trophic importance of the contributions of the different habitats, as well as on trophic relationships between the key consumers and on how these vary over space and time, is essential. This level of detail is however still not well understood for most coastal seascapes. As a consequence, models of estuary functioning, evaluations of status and vulnerability, and understanding of ecosystem value are usually extrapolated from other studies, often from systems separated by large distances and with unknown physical or biological similarities to the estuary in question. This can lead to the mismanagement of fishery species and/or used habitats.

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Appendix 5. Pre-requisites for the development of achievable measures of fisheries benefits of habitat repair and revitalisation actions Northern Australia's coasts

Marcus Sheaves

Executive summary

i. Healthy coastal wetlands and estuaries (ECWs), and the habitats that comprise them, play vital roles in supporting coastal food webs and fisheries production acting as critical feeding, nursery and reproductive areas for many important species. However, Queensland's ECWs are severely degraded due to the impact of a diversity of anthropogenic stressors. As a consequence, ECW function has been compromised by substantial losses of some of Queensland's most productive of aquatic habitats. As a result, careful management and repair and revitalisation actions are urgently needed. These actions need to be prioritised and their success evaluated. Consequently, this study investigates how the value of coastal wetlands and estuaries can be measured in robust, valid and meaningful ways.

ii. While accurate, robust and valid measures of the value of coastal wetlands and estuaries are critical for management, at present valid, defensible measures of the value of different units are not available. These measures need to be relevant at the scale of unit or outcome to be evaluated, broadly meaningful and easy to communicate to end-users. Quality estimates of the production of exploited species are of particular value in a fisheries context. However, a substantial body of data are needed for the calculation of production estimates. Standing stock estimates are more achievable and, as long as their limitations are understood, can provide useful measures of estuary or coastal wetland habitat value that are easily understood and easily communicated.

iii. Most common sampling approaches are unsuitable for estimating density per unit area, the most fundamental component of fisheries production estimates. However, cast nets and beam trawls have proven effective for providing suitable data on penaeid prawns and bait fish in north Queensland estuaries, and have the potential to be developed into useful estimates of production per area of tropical estuary or coastal wetland habitat. Substantial data sets of these types exist but additional research and development are required before such data can usefully be related to specific areas of estuary or coastal wetland. Because samples from methods suitable for larger species cannot be related to an area fished they cannot provide spatially explicit estimates but only estimates relative to the effort needed to catch the fish.

iv. Data sets of the types required as a basis for estimates of standing stock already exist but need additional research and development before they can usefully be related to specific areas of estuary or coastal wetland. If we are to fully account for the value of these habitats to fisheries it is important to understand the ecological context around the species-productivity and species-habitat linkages, and to consider all the variables that influence these linkages.

v. Substantial additional studies are required to produce workable and valid estimates of standing stock that are truly representative.

1. Introduction

1.1. Background

1.1.1. The value of coastal wetlands and estuaries

Healthy coastal wetlands and estuaries (ECWs), and the habitats that comprise them, play vital roles in supporting coastal food webs and fisheries production (Weinstein & Litvin 2016). For instance, in northern Australia important fisheries species such as barramundi (*Lates calcarifer*), mangrove jack (*Lutjanus argentimaculatus*), banana prawns (*Fenneropenaeus merguiensis*) and mud crabs (*Scylla serrata*) are profoundly estuary dependent (Robertson & Duke 1987, Sheaves et al. 2007b). This dependence results from the reliance of critical life history phases on habitats such as mangroves (Robertson & Duke 1987), seagrass (Coles et al. 1987, Watson et al. 1993) and salt marshes (Russell & Garrett 1983), on the occurrence of suitable environmental conditions in these habitats (Sheaves 1996), and on the primary production (Hughes et al. 2009) and integration of allochthonous nutrient subsidies (Abrantes & Sheaves 2008) that occurs there. Consequently, maintaining and improving ECW function and quality is the critical to ensuring continued fisheries productivity (Walker et al. 2004).

1.1.2. Status of Queensland's coastal wetlands and estuaries

Queensland's ECWs are severely degraded, with much of the original lowland forest (Moore et al. 2007) and large areas of freshwater wetlands to brackish swamps (Russell et al. 2011, Saintilan & Rogers 2013) converted to agricultural land over the last 100 years. About 8.5% of the total area of estuaries in the Great Barrier Reef region has been lost since European settlement (Sheaves et al. 2014). The historical wetland and riparian loss continues today (Sheaves et al. 2014). Much of this deterioration is the result of loss of tidal wetland area, including mangroves and saltmarsh, and this is compounded by large areas from which fisheries species are excluded by barriers (e.g. weirs, tidal exclusion bunds, sand dams, and road and rail crossings). Connectivity is further reduced by inefficient culverts and crossings, and macrophyte chokes.

1.1.3. Threats to Queensland's of coastal wetlands and estuaries

Queensland's ECWs are impacted by a diversity of anthropogenic stressors, including agricultural expanding, development of coastal commercial activities and ports, and increasingly urbanisation (Grech et al. 2011), all of which generate a complexity of consequences and outcomes. These include increasing sediment loads (Alongi & McKinnon 2005), declining estuarine water quality (Cox et al. 2005), increasing exposure to acid sulphate soils and blackwater events (Powell & Martens 2005, Wong et al. 2010, Hladyz et al. 2011), and toxic cyanobacteria blooms (Albert et al. 2005). All of these pose risks for the condition of inshore biotic assemblages and their habitats (Fabricius et al. 2005).

1.1.4. Consequences

The consequences are far reaching. ECW function been compromised by substantial losses of some of Queensland's most productive of aquatic habitats (Boys et al. 2012, Heatherington & Bishop 2012). These impacts are compounded by impeded hydrological and biological connectivity (Sheaves & Johnston 2008) that interrupting the delivery of allochthonous nutrients and limits access for fauna to highly productive wetland areas, compromising nursery ground value (Sheaves et al. 2014).

1.1.5. Repair and Revitalisation

The widespread damage to Queensland's ECWs means there is an urgent need for their remediation (Sheaves et al. 2014, Creighton et al. 2015). In fact, repairing these key ecosystems can lead to a raft of benefits: increased fisheries output and ecosystem resilience, enhanced food security and livelihoods, and the protection of ecological assets of national and global significance (Sheaves et al. 2014). Works are underway to repair and revitalise wetlands and estuaries along the Great Barrier Reef (GBR) coast. The success of these repair initiatives requires that they are well targeted, carefully prioritised and their success evaluated. Fundamental to this is the need to be able to value ECW services and ensure that outcomes are measureable in meaningful ways (Wegscheidl et al. in review).

1.2. Objectives

The aims of this study is to investigate how the value of northern Australia's coastal wetlands and estuaries can be measured in robust, valid and meaningful ways. Consequently, we investigated the pre-requisites for the development of achievable measures of fisheries benefits of habitat repair and revitalisation actions. In doing this we (a) examine the need for measures of ECW value and what form appropriate estimates should take, (b) assess appropriate methods for collecting necessary data and the extent of data currently available, and (c) determine the additional studies needed to convert the available data into useable measures of fisheries benefits.

2. Achievable, Robust and Valid Measures of Estuary and Coastal Wetland Value

Summary: *While accurate, robust and valid measures of the value of coastal wetlands and estuaries are critical for management, at present valid, defensible measures of the value of different units are not available. These measures need to be relevant at the scale of unit or outcome to be evaluated, broadly meaningful and easy to communicate to end-users. Quality estimates of the production of exploited species are of particular value in a fisheries context. However, a substantial body of data are needed for the calculation of production estimates. Standing stock estimates are more achievable and, as long as their limitations are understood, can provide useful measures of estuary or coastal wetland habitat value that are easily understood and easily communicated.*

2.1. Background

The services provided by ecosystems are critical to the Earth's functioning and contribute directly (e.g. food security) and indirectly to human welfare and economies (Costanza et al. 1997). ECWs are particularly important because of the diversity of services they provide (e.g. fisheries, nursery grounds, filtering and detoxification, blue carbon) (Barbier 2000). Despite arguments that we should protect wetlands and estuaries purely on grounds of their intrinsic ecological value we still need to value them, both because there are equally valid moral arguments relating to the potential food security values stemming from altering wetlands (Costanza et al. 1997) and because arguments about intrinsic ecological value are difficult for decision makers to evaluate when balanced against tangible economics (Freeman 1991). In fact, the decisions society makes about ecosystems imply valuation (Costanza et al. 1997); as long as we are forced to make choices we are intrinsically basing those choices on some measure of value (Costanza & Folke 1997).

2.2. Appropriate estimates of ECW value

Accurate, robust and valid measures of the value of ECWs are critical for many reasons. For instance, comprehensive estimates are needed to ensure the values of ECWs are given appropriate weight in policy and management decisions (Costanza et al. 1997), and so offset and ecosystem repair can be prioritised and their outcomes measured (Sheaves et al. 2014, Creighton et al. 2015). However, there are many problems in estimating the value of ecosystem services of wetlands and estuaries because their values are multifaceted and interact in complex ways (Costanza et al. 1997), with high levels of connectivity among components meaning management of the entire seascape will usually be necessary to preserve synergistic effects (Barbier 2000). However, the basic underpinnings of estimates are simple; whether the final output is a complex ecological-economic model (Barbier 2007) or an estimate of the value of a particular habitat or area to be managed or repaired, the basic requirements are for:

a) precise estimates of the areal extent of the units of interest and the habitats that comprise them (McArthur & Boland 2006), and
b) high quality measures of the value of the particular units (habitats, estuary reaches etc.) (Minello et al. 2008, Minello et al. 2012).

Recent extensive and detailed mapping (e.g. by the Queensland Wetland program) means that appropriate high quality mapping is available. However, at present valid, defensible measures of the value of different units are not available. These measures could take many forms but only a few fit the key criteria of being (1) measureable at the scale of unit or outcome to be evaluated, (2) broadly meaningful and (3) easy to communicate to end-users. In this regard, high quality estimates of the ***production*** (the expected increase in biomass over time for a population (Chapman 1978)) ***of exploited species*** are of particular value in a fisheries context (e.g. McArthur & Boland 2006, Barbier 2007), because they provide detailed information on the value of a unit, such as an estuarine wetland, by detailing the amount of biomass produced from the wetland over a specific time period. Not only is the production per unit area of well recognised species directly relevant to end users, and so easy to communicate, but it provides the added advantage of integrating across complex factors such as connectivity and nursery ground provision that are often hard to assign a defensible values to (Costanza et al. 2006).

However, a substantial body of data are needed for the calculation of production estimates for a species from a single habitat (Fig. A5-1), including data on:

(i) the extent of each habitat type,
(ii) replicate small-scale estimates of density of the species within the habitat,

(iii) size frequency of the species,
(iv) size-weight relationships, and
(v) growth and mortality rates.

Data on (i) and (ii) allow ***population abundance*** to be estimated, while (iii) and (iv) allow abundance to be converted to ***standing stock biomass*** (the biomass of a species in a defined area at a point in time (Rozas et al. 2005)) – the most basic measure of production. Sampling standing stock over time and combining it with growth rate and mortality data (v) allows abundance estimates to be converted to ***estimates of biomass production*** over a period of time (e.g. annually) (Minello et al. 2008). As an indication of the amount and complexity of data required; determining habitat-specific density patterns (e.g. on a monthly basis) require extensive, long-term data, as well as independent validation (Minello et al. 2008). Assessing growth and mortality rates is even more complex. Amassing such extensive data requires substantial resources so is only possible for areas such as the US Gulf Coast, where extensive data collections have occurred over an extended period of time (Minello et al. 2012).

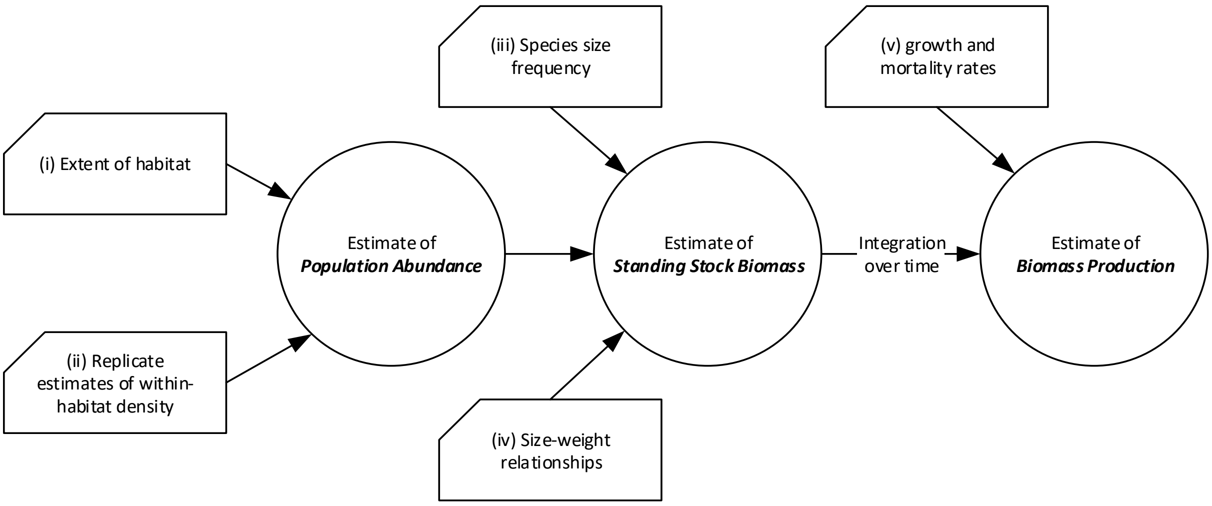

Figure A5-1. Steps needed for the calculation of production estimates for a species from a single habitat.

Estimates of ***biomass production over time*** provide a full picture of the production from a habitat or area integrated over the full year, so provide the most comprehensive way to assess value. However, in most cases there will be too many gaps in the necessary knowledge to allow development of these estimates over the short term. Consequently, initial work should be directed to producing high quality estimates of ***standing stock biomass***. Although not integrated over time, and so not providing direct information on the increase in biomass in a unit of time, standing stock estimates are readily achievable and can provide useful measures of estuary or coastal wetland habitat value that are easily understood and easily communicated, as long as their limitations as snapshots in time are recognised. For a particular point in time standing stock biomass provides a well-established and valid basis for evaluating the contributions from ECW habitats and a basic measure of how those contributions are likely to change under different scenarios.

3. Approaches for Estimating Production from ECWs

Summary: *Most common sampling approaches are unsuitable for estimating density per unit area, the most fundamental component of fisheries production estimates. However, cast nets and beam trawls have proven effective for providing suitable data on penaeid prawns and bait fish in north Queensland estuaries, and have the potential to be developed into useful estimates of production per area of tropical estuary or coastal wetland habitat. Substantial data sets of these types exist but additional research and development are required before such data can usefully be related to specific areas of estuary or coastal wetland. Because samples from methods suitable for larger species cannot be related to an area fished they cannot provide spatially explicit estimates but only estimates relative to the effort needed to catch the fish.*

3.1. Background

The most fundamental component of fisheries production are measures of ***density per unit area***; the basic component of standing stock and production. There are many methods to sample fisheries species to provide catch-per-unit-effort (CPUE) data (e.g. Table 1). However, few sample a definable area of water, a basic requirement to enable the conversion of CPUE into a measure of density. Of those that do, many are limited in only being deployable in a few specific situations, restricting their usefulness for comparisons among habitat types (Sheaves 1995, Baker & Minello 2011). Even those that have been successfully used to provide estimates of density (e.g. drop samplers (Minello et al. 2008), pop nets (Serafy et al. 1988), cast nets (Sheaves et al. in press-a)) have limitations. Drop samplers and pop nets are limited to shallow water applications and, because operators need to enter the water to harvest catches, they are unsuitable in areas, such as tropical Australia, where estuarine crocodiles are prevalent. ***Cast nets*** can be used without the operator entering the water but have the limitations of being less effective on large fish, which may be able to escape as the net sinks, and in not providing a completely consistent sampling area. The use of experienced operators can improve the consistency of the area sampled by cast nets (Johnston & Sheaves 2007) and they have proved successful for estimating densities of smaller fisheries species in tropical estuaries

(Sheaves et al. 2007b, Sheaves & Johnston 2009). ***Beam trawls*** have also proved effective in providing estimates of density per unit area, particularly for sampling deeper open bottom habitats including seagrass beds (e.g. Watson et al. 1993).

3.2. Details of appropriate gears

Cast nets are particularly useful for sampling shrimps and prawns because their escape response tends to be tactile rather than visual (Watson et al. 1992), meaning they show little response until the net actually covers them, and even if they are alarmed their escape direction tends to be random (Watson et al. 1992, Xiao & Greenwood 1993). Cast nets are particularly useful in the structurally complex habitats of tropical estuaries, where submerged timber 'snags' are common (Sheaves 1992), because they can be used across most habitats (Sheaves et al. 2007a, Johnston & Sheaves 2008). In particular, they can even be deployed directly adjacent to snags, something not possible with most other netting approaches. Thus, on balance cast nets provide a simple way to estimate density of penaeids, such as the mangrove associated banana prawn, *Fenneropenaeus merguiensis*, in many tropical ECW situations (Sheaves et al. in press-a).

Although not as reliably effective on fish, because the possibility of avoidance is higher, cast nets are still one of the more effective ways of sampling smaller fish in tropical estuaries (e.g. Sheaves et al. 2007b, Sheaves & Johnston 2009) and so provide some of the better estimates of density for baitfish species.

Beam trawls can provide estimates of density via the swept-area method but suffer the restrictions that they are difficult to operate in very shallow water and can only be used in areas lacking hard structures such as snags or rocks. However, beam trawls have proven very useful in estimating densities of seagrass-associated pawn species such as *Penaeus esculentus*, *P. semisulcatus* and *Metapenaeus endeavouri* (Watson et al. 1993). Consequently, samples of penaeid prawns and baitfish captured with cast nets and beam trawls have the potential to be developed into useful estimates of production per area of ECW habitat.

Estimating the production of larger species is more difficult, and tends to rely on CPUE rather than density per unit area – making it difficult to meaningfully translate estimates to variables such as the area of wetland. Traditionally stocks of species like barramundi, *Lates calcarifer*, have been assessed on the basis of commercial catches from the **gill net** fishery (e.g. Staunton-Smith et al. 2004). These data can provide indices of abundance but, because of the diversity of factors affecting gill net catches and because gill net catches cannot be related to a specific fished area (Table), such indices are only really suitable for estimates of relative rather than absolute production. Consequently, because of the ability to obtain estimates of biomass per unit area, measures of the production of prawns and baitfish provide the greatest opportunity for development as fisheries-based indices of the value of ECWs.

3.3. Available data

There are already substantial data sets of biomass per unit area for *F. merguiensis* and baitfish such as herring from cast netting (Sheaves et al. in press-a), with data from 28 north Queensland estuaries. Similarly, there are extensive beam trawl data for various penaeid species from north Queensland seagrass beds from 1984 to the present day (Watson et al. 1993) as well as for *F. merguiensis* from the Fitzroy River (Sheaves unpublished data). While data such as these can be used as the basis for useful estimates of production, additional research and development are needed before they can usefully be related to specific areas of ECW.

Table 1. Comparison of the effectiveness of some gears commonly used to sample estuary and wetland fisheries species.

Gear	Measure of area?	Sampling areas	Comments
Beam trawl	Swept area	Smooth unstructured bottoms	Suitable for prawns because of random escape response. Do not enclose so inefficient for mobile fish species. Difficult to deploy in shallow water.
Cast nets	Enclosed radius	Many habitats, can be used close to structure	Can be used across many habitats except for heavily structured ones. Problems that area sampled can vary and that more mobile species can escape. Most suitable for prawns because of random escape response.
Drop sampler	Enclosed radius	Open areas plus light vegetation	Accurate sample once deployed but vessel needs to be deployed close to the sampling location potentially causing fish to move away. Only usable in very shallow water.
Electrofisher	no	Most habitats	Only effective in very low salinities.
Fish traps	no	most habitats	Attract fish with bait so unsuitable for density estimates
Fyke nets	no	blocking drains	Used to block channels draining areas of wetland so difficult to define area sampled.
Gill nets	no	Unstructured open water	Designed to intercept moving fish so no way to relate catch to area and efficiency dependent on day-to-day behaviour.
Lift /pop nets	Enclosed radius	Open areas and aquatic vegetation	Need to be set on the substrate prior to sampling so may bias samples. Only useable in very shallow water. Operators need to enter water so unsuitable in crocodile risk areas.
Seine nets	Swept area	Smooth unstructured bottoms	Only useable on smooth bottoms with consolidated sediments. Also need to be deployed adjacent to a shoreline.
Video (baited)	no	Most habitats	Area ‘fished’ difficult to define because bait used to attract.
Video (unbaited)	no	Most habitats	Main limitations are water clarity and difficulty in defining area sampled. Most useful for detecting presence in a habitat.

4. Additional Studies Needed to Develop Useable Measures

Summary: *Data sets of the types required as a basis for estimates of standing stock already exist but need additional research and development before they can usefully be related to specific areas of estuary or coastal wetland. If we are to fully account for the value of these habitats to fisheries it is important to understand the ecological context around the species-productivity and species-habitat linkages, and to consider all the variables that influence these linkages.*

4.1. Background

Using the production of species of commercial and recreational importance as indicators of the productivity of ECW habitats has the substantial advantages of being broadly meaningful and easy to communicate to end-users. However, there are three key considerations to be taken into account (i) the ecological context of the species and its link to productivity, (ii) the state of understanding of species and community ecology, and (iii) actually linking estimates of biomass density (i.e. standing stock) to areas of habitat in a meaningful and valid way.

4.2. The ecological context

Not only are there readily available methods for sampling biomass per unit area of penaeid prawns that can provide valid data for estimating standing stock, but prawn's ecological context makes them good candidates for linking their productivity to ECW habitat area. The food webs leading to penaeids, such as banana prawns *F. merguiensis*, are relatively simple and well understood (Abrantes & Sheaves 2009, Abrantes & Sheaves 2010). These food webs are short with simple links the productivity of the habitats they occupy, enable direct links to be made between *F. merguiensis*, and the ECW resources that support its productivity.

In contrast, not only is it difficult to obtain data on density per unit area of large fish predators such as barramundi, *L. calcarifer*, but the food webs leading to high trophic level predators such as this are much more complex, making it much more difficult to their biomass to particular resources. In fact, highly mobile species like *L. calcarifer* are likely to depend on a complex mosaic of interlinked habitats throughout their life history (Nagelkerken et al. 2015) meaning more integrated measures of the value of wetlands to higher level predators is needed.

One approach is to overcoming the problems with obtaining meaningful estimates for large predators is to use the density of easily measured surrogate species (e.g. Lewandowski et al. 2010, Mellin et al. 2011, Fontaine et al. 2015) as relevant indicators of the support that ECWs provide for large predators. Banana prawns productivity provides one obvious option because they are key prey for many predators such as *L. calcarifer* (Robertson 1988). A second alternative is the density of planktivores, also key components of food webs linking primary productivity to high order predators. At least for the cast net data, estimates of planktivore biomass are available for the same sets of estuaries covered by the *F. merguiensis* data (Sheaves et al. in press-a), so potentially providing an additional valuable tool for measuring ECW productivity that can be developed with the same work required to operationalise the *F. merguiensis* data.

4.3. The state of understanding of species and community ecology

Even for well studies species there is often a deficit in the information needed to make the species-productivity link; this limits the reliability with which biomass production can be linked to particular habitat units. For example, even though the issues seem reasonably straightforward for species like *F. merguiensis,* this is not necessarily the case. Commercial fisheries for banana prawns *F merguiensis* occur in offshore waters but their juveniles are strongly associated with mangrove estuaries (Vance et al. 1990), meaning there appears to be a direct link with mangrove wetlands. Indeed, offshore catches of adult *F. merguiensis*, are correlated with the extent of mangrove forests (Manson et al. 2005). However, the extent to which the apparent relationship between juvenile penaeids and mangroves reflects specific utilisation of mangroves, or just the use of shallow, organically rich, muddy habitats has been questioned (Lee 2004). A study focussing on juvenile *F. merguiensis* within 30 mangrove estuaries spanning 650km of the coast of north-eastern Australia (Sheaves et al. 2012) assessed the prawn-mangrove relationship within estuaries. The study indicated that (i) at the among-estuaries scale mangrove extent appeared to influence CPUE but was extensively confounded with the effects of two non-mangrove variables; intertidal extent and substrate type, (ii) connectivity with mangrove forests was not influential, pointing to the likely importance of the non-mangrove variables rather than mangrove extent, and (iii) at the within-estuary scale CPUE showed no correlation with mangrove variables but rather correlated with the extent of shallow water, again implicating the role of a complex of ECW habitats in supporting juvenile *F. merguiensis* populations. This idea is strengthened by studies that indicate that wetlands where mangroves are not the dominant vegetation are also important habitats for juvenile *F. merguiensis* (Sheaves et al. 2007b). Consequently, there is a clear need to develop a more explicit understanding of the ways in which coastal wetlands support even those species such as *F. merguiensis* that are well recognised as having strong links to mangroves. Developing a more sophisticated knowledge of the specific ways that ECW habitats influence fisheries populations is clearly critical if we are to fully account for the value of these habitats to fisheries.

4.4. Meaningfully linking estimates of biomass density to areas of habitat

Sampling methods such as cast nets and beam trawls can provide reliable estimates of density per unit area for the habitats in which they can be deployed. However, a number of steps are needed to convert these to an estimate of standing stock in a unit of interest.

The problem is relatively simple if the unit of interest is a single habitat type where biomass density can be assumed to be, on average, homogeneous. The steps then are straight forward (Fig. A5-2):

(1) Collect sufficient biomass density samples to ensure that:
    a. The pattern of within habitat variability is well understood. This will allow evaluation of the extent to which the assumption that the species biomass density is homogenous across the habitat type, and so whether it is reasonable to use an average value (e.g. the mean biomass) as an estimate for the whole habitat.
    b. The mean biomass is accurately and precisely estimated;

(2) Use this mean biomass as an estimate of the biomass per unit area for the habitat, and the estimated variability to provide a measure of uncertainty about the estimate.

However, because ECWs are composed of mosaics of habitats the problem will usually be more complex. Take for instance the problem of estimating standing stock for an estuary reach. The reach will (i) comprise a number of different habitats, each with intrinsically different densities of the target species, and (ii) include habitats that are efficiently sampled using the particular gear and those that aren't. Additional steps are necessary (Fig. A5-2):

(3) Areas in which the target species are well sampled can be treated as in (1) above.

(4) Comparable estimates will need to be made for areas in which sampling with the standard gear is inefficient. This will often be difficult. For instance, although cast nets are inefficient for structurally complex habitats like fallen timber other capture approaches are also unsuitable. While there is no perfect approach to solving this problem there are workable solutions. One is to use a technique such as unbaited video (e.g. Sheaves et al. in press-b) to determine the extent to which the species utilises the difficult-to-sample habitat and use this information to construct approximate biomass density estimates for those habitats, together with measures of the uncertainty involved in the estimates.

(5) Once the total area of each habitat type is known, standing stock estimates for the whole estuary can be constructed.

Although estimates will never be perfect such protocols can provide useful approximations of standing stock that provide well founded estimates with a defined level of uncertainty.

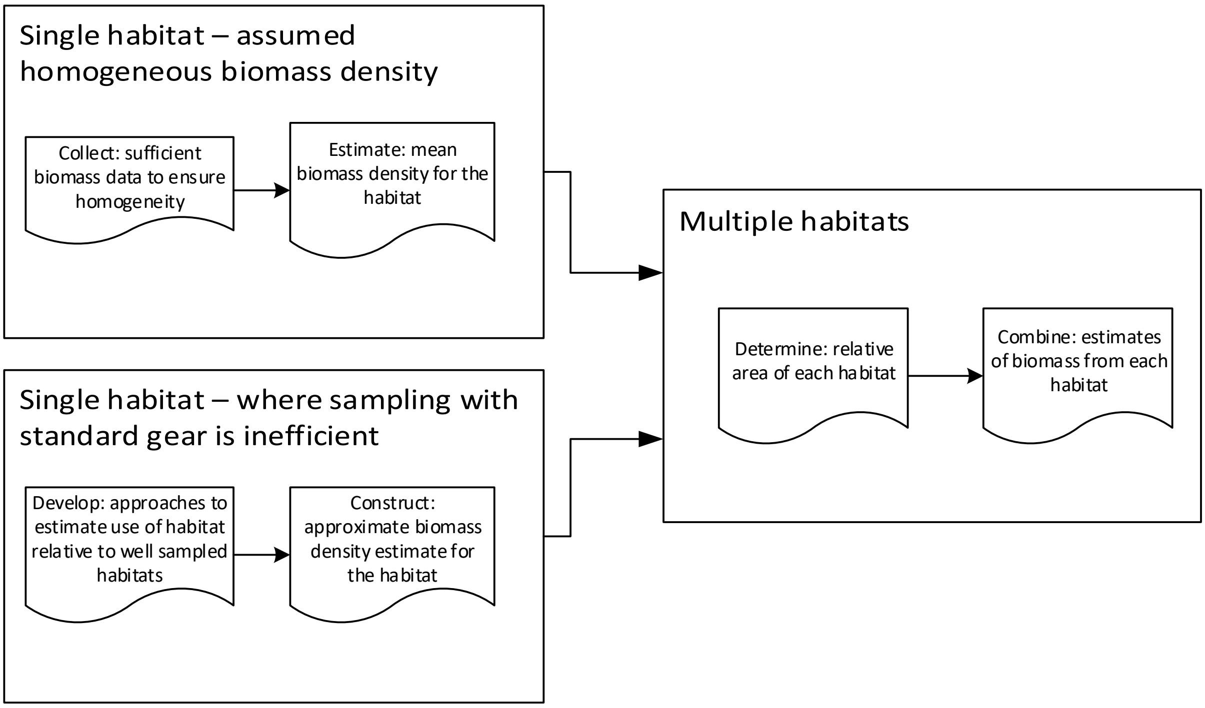

Figure A5-2. Steps needed to convert biomass per unit area to an estimate of standing stock.

5. Studies to address Key Knowledge Gaps

Although the basic information on biomass density is available, clearly, substantial research is needed before these can be converted to valid estimates of standing stock. This includes both the careful and comprehensive sampling needed to provide estimates for all the habitats well-sampled by the sampling gear employed, detailed estimates of the extent of each habitat type, and extensive studies to develop the best possible estimates for habitats that cannot be sampled using conventional gears. There is also the need to develop a more sophisticated knowledge of the specific ways that ECW habitats influence fisheries populations is clearly critical if we are to fully account for the value of these habitats to fisheries.

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Appendix 6. Process zone utilisation by Australian fisheries species

Table A6-1. Process zone utilisation by juveniles and adults of Australian fisheries species. Nursery and Adult profile categories indicate the range of process zones normally utilised by juveniles and adults. Note: Information is based on summarised data and there may be limited occurrences outside the limits of these groups.

Group	Common name	*Species*	Juveniles: freshwater	Juveniles: transitional wetlands	Juveniles: estuary	Juv: coasts, bays, headlands. beaches	Juv: inshore waters (incl. coral reefs)	Juveniles: offshore waters	***Nursery group***	Adults: freshwater	Adults: transitional wetlands	Adults: estuary	Adults: coasts, bays, headlands, beaches	Adults: inshore waters (incl. coral reefs)	Adults: offshore waters	***Adult group***
crustacean	whitetail bug	*Ibacus alticrenatus*				✓	✓		*coastal*				✓	✓		*coastal inshore*
crustacean	smooth bug	*Ibacus chacei*				✓	✓		*coastal*				✓	✓		*coastal inshore*
crustacean	eastern Balmain bug	*Ibacus peronii*			✓	✓	✓		*estuary inshore*				✓	✓		*coastal inshore*
crustacean	southern rock lobster	*Jasus edwardsii*				✓	✓		*coastal*				✓	✓	✓	*coastal offshore*
crustacean	eastern rock lobster	*Jasus verreauxi*				✓			*coastal*				✓	✓	✓	*coastal offshore*
crustacean	greasyback prawn	*Metapenaeus bennettae*		✓	✓				*estuary*			✓	✓	✓		*estuary inshore*

Group	**Common name**	***Species***	Juveniles: freshwater	Juveniles: transitional wetlands	Juveniles: estuary	Juv: coasts, bays, headlands. beaches	Juv: inshore waters (incl. coral reefs)	Juveniles: offshore waters	***Nursery group***	Adults: freshwater	Adults: transitional wetlands	Adults: estuary	Adults: coasts, bays, headlands, beaches	Adults: inshore waters (incl. coral reefs)	Adults: offshore waters	***Adult group***
crustacean	blue Endeavour prawn	*Metapenaeus endeavouri*			✓	✓			*estuary coastal*					✓		*coastal inshore*
crustacean	red Endeavour prawn	*Metapenaeus ensis*			✓	✓			*estuary coastal*					✓		*coastal inshore*
crustacean	school prawn	*Metapenaeus macleayi*		✓	✓				*estuary*			✓	✓	✓		*estuary inshore*
crustacean	western rock lobster	*Panulirus cygnus*				✓	✓		*coastal*				✓	✓	✓	*coastal offshore*
crustacean	ornate rock lobster	*Panulirus ornatus*			✓	✓	✓		*estuary inshore*				✓	✓	✓	*coastal offshore*
crustacean	painted rock lobster	*Panulirus versicolor*				✓	✓		*coastal*				✓	✓	✓	*coastal offshore*
crustacean	brown tiger prawn	*Penaeus esculentus*			✓	✓			*estuary coastal*					✓		*coastal inshore*
crustacean	red-legged banana prawn	*Penaeus indicus*		✓	✓				*estuary*					✓		*coastal inshore*
crustacean	western king prawn	*Penaeus latisulcatus*			✓	✓			*estuary coastal*						✓	*offshore*
crustacean	red spot king prawn	*Penaeus longistylus*			✓	✓	✓		*estuary inshore*					✓		*coastal inshore*
crustacean	white banana prawn	*Penaeus merguiensis*		✓	✓				*estuary*					✓		*coastal inshore*

Group	Common name	*Species*	Juveniles: freshwater	Juveniles: transitional wetlands	Juveniles: estuary	Juv: coasts, bays, headlands. beaches	Juv: inshore waters (incl. coral reefs)	Juveniles: offshore waters	***Nursery group***	Adults: freshwater	Adults: transitional wetlands	Adults: estuary	Adults: coasts, bays, headlands, beaches	Adults: inshore waters (incl. coral reefs)	Adults: offshore waters	***Adult group***
crustacean	giant tiger prawn	*Penaeus monodon*			✓	✓			*estuary coastal*					✓		*coastal inshore*
crustacean	eastern king prawn	*Penaeus plebejus*			✓	✓	✓		*estuary inshore*					✓	✓	*coastal offshore*
crustacean	grooved tiger prawn	*Penaeus semisulcatus*			✓	✓			*estuary coastal*					✓		*coastal inshore*
crustacean	blue swimmer crab	*Portunus pelagicus*		✓					*estuary*			✓	✓	✓		*estuary inshore*
crustacean	spanner crab	*Ranina ranina*				✓	✓		*coastal*				✓	✓	✓	*coastal offshore*
crustacean	brown mud crab	*Scylla olivacea*		✓	✓				*estuary*			✓	✓	✓		*estuary inshore*
crustacean	mud crab	*Scylla serrata*		✓	✓				*estuary*			✓	✓	✓		*estuary inshore*
crustacean	mudbug	*Thenus indicus*			✓	✓			*estuary coastal*				✓	✓		*coastal inshore*
crustacean	sandbug	*Thenus orientalis*				✓	✓		*coastal*				✓	✓		*coastal inshore*
fish	Barred longtom	*Ablennes hians*					✓	✓						✓	✓	
fish	yellowfin bream	*Acanthopagrus australis*		✓	✓				*estuary*		✓	✓	✓	✓		*estuary inshore*

Group	Common name	*Species*	Juveniles: freshwater	Juveniles: transitional wetlands	Juveniles: estuary	Juv: coasts, bays, headlands. beaches	Juv: inshore waters (incl. coral reefs)	Juveniles: offshore waters	***Nursery group***	Adults: freshwater	Adults: transitional wetlands	Adults: estuary	Adults: coasts, bays, headlands, beaches	Adults: inshore waters (incl. coral reefs)	Adults: offshore waters	***Adult group***
fish	black bream	*Acanthopagrus butcheri*		✓	✓				*estuary*		✓	✓				*estuary coastal*
fish	western yellowfin bream	*Acanthopagrus latus*		✓	✓				*estuary*		✓	✓	✓			*estuary coastal*
fish	pikey bream	*Acanthopagrus pacificus*		✓	✓				*estuary*		✓	✓	✓			*estuary coastal*
fish	northwest black bream	*Acanthopagrus palmaris*		✓	✓				*estuary*		✓	✓	✓			*estuary coastal*
fish	blue groper	*Achoerodus viridis*			✓	✓	✓		*estuary inshore*				✓	✓		*coastal inshore*
fish	bonefish	*Albula glossodonta*			✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
	Pennantfish	*Alectes ciliaris*				✓	✓						✓	✓		
	Diamond trevally	*Alectis indica*				✓	✓						✓	✓		
fish	yellow-eye mullet	*Aldrichetta forsteri*		✓	✓				*estuary*		✓	✓	✓			*estuary coastal*
fish	black oreo	*Allocyttus niger*						✓	*offshore*						✓	*offshore*
fish	warty oreo	*Allocyttus verrucosus*						✓	*offshore*						✓	*offshore*
fish	mulloway	*Argyrosomus japonicus*		✓	✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
	Green jobfish	*Aprion virescens*					✓	✓						✓	✓	

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fish	tommy ruff	*Arripis georgianum*			✓	✓			*estuary coastal*			✓	✓			*estuary coastal*
fish	Australian salmon	*Arripis trutta*			✓	✓			*estuary coastal*				✓			*coastal inshore*
fish	Western Austalian salmon	*Arripis truttaceus*			✓	✓			*estuary coastal*				✓			*coastal inshore*
fish	teraglin	*Atractoscion aequidens*					✓		*inshore*					✓		*coastal inshore*
fish	Frigate mackerel tuna	*Auxis thazard*				✓	✓	✓					✓	✓	✓	
fish	Goldspotted wrasse	*Bodianus perditio*					✓							✓		
fish	Longnose trevally	*Carangoides chrysophrys*					✓							✓		
fish	Gold-spot trevally	*Carangoides fulvoguttatus*				✓	✓						✓	✓		
fish	Bludger trevally	*Carangoides gymnostethus*				✓								✓		
fish	Blue spotted trevally	*Caranx bucculentus*					✓							✓		
fish	giant trevally	*Caranx ignobilis*	✓	✓	✓	✓			*fresh estuary*			✓	✓	✓		*estuary inshore*
	Bluefin trevally	*Caranx megalympus*					✓							✓		
fish	Papuan trevally	*Caranx papuensis*	✓	✓	✓	✓			*fresh estuary*			✓	✓	✓		*estuary inshore*
fish	bigeye trevally	*Caranx sexfasciatus*			✓	✓			*estuary coastal*				✓	✓		*coastal inshore*

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fish	redfish	*Centroberyx affinis*			✓	✓	✓		*estuary inshore*					✓	✓	*coastal offshore*
	Milkfish	*Chanos chanos*			✓	✓	✓					✓	✓	✓		
fish	red morwong	*Cheilodactylus fuscus*				✓	✓		*coastal*				✓	✓		*coastal inshore*
fish	banded morwong	*Cheilodactylus spectabilis*				✓	✓		*coastal*				✓	✓		*coastal inshore*
	Green finned parrotfish	*Chlorurus sordidus*					✓							✓		
fish	blue tuskfish	*Choerodon cyanodus*				✓	✓		*coastal*				✓	✓		*coastal inshore*
fish	baldchin groper	*Choerodon rubescens*				✓	✓		*coastal*				✓	✓		*coastal inshore*
fish	blackspot tuskfish	*Choerodon schoenleinii*				✓	✓		*coastal*				✓	✓		*coastal inshore*
	Venus tuskfish	*Choerodon venustus*				✓	✓						✓	✓		
fish	snapper	*Chrysophrys auratus*			✓	✓	✓		*estuary inshore*				✓	✓		*coastal inshore*
fish	cobbler	*Cnidoglanis macrocephalus*		✓					*estuary*			✓	✓			*estuary coastal*
fish	mahi mahi (dolphinfish)	*Coryphaena hippurus*						✓	*offshore*						✓	*offshore*
	Watsons leaping bonito	*Cybiosarda elegans*				✓	✓						✓	✓		

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	Fringe-eyed flathead	*Cymbacephalus nematophthalmus*			✓	✓						✓	✓			
	Dusky morwong	*Dactylophora nigricans*										✓	✓	✓		
fish	flying gurnard	*Dactyloptena orientalis*			✓	✓			*estuary coastal*			✓	✓			*estuary coastal*
	Painted sweetlip	*Diagramma pictum*				✓	✓						✓	✓		
fish	long-finned pike	*Dinolestes lewini*			✓	✓			*estuary coastal*			✓	✓			*estuary coastal*
	Sicklefish	*Drepane punctata*			✓							✓				
	rainbow runner	*Elagatis bipinnulata*												✓	✓	
fish	blue threadfin salmon	*Eleutheronema tetradactylum*		✓	✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
	Diamondscale mullet	*Ellochelon vaigiensis*			✓	✓						✓	✓			
fish	giant herring	*Elops hawaiensis*		✓	✓				*estuary*			✓	✓	✓		*estuary inshore*
fish	anchovy	*Engraulis australis*		✓	✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
fish	breaksea cod	*Epinephelides armatus*				✓			*coastal*				✓	✓		*coastal inshore*
fish	yellow-spotted rock cod	*Epniephelus areolatus*				✓	✓		*coastal*				✓	✓		*coastal inshore*

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fish	gold-spot estuary cod	*Epniephelus coioides*			✓	✓			*estuary coastal*				✓	✓		*coastal inshore*
fish	Malabar cod	*Epniephelus malabaricus*		✓	✓	✓			*estuary coastal*				✓	✓		*coastal inshore*
fish	Rankin's rock cod	*Epniephelus multiontatus*				✓	✓		*coastal*				✓	✓		*coastal inshore*
fish	mackerel tuna	*Euthynnus affinis*				✓	✓		*coastal*				✓	✓		*coastal inshore*
fish	pink ling	*Genypterus blacodes*					✓	✓	*offshore*					✓	✓	*coastal offshore*
fish	black drummer	*Girella elevata*				✓			*coastal*				✓			*coastal inshore*
fish	luderick	*Girella tricuspidata*				✓			*coastal*			✓	✓			*estuary coastal*
fish	westralian jewfish	*Glaucosoma hebraicum*					✓		*inshore*					✓	✓	*coastal offshore*
fish	pearl perch	*Glaucosoma scapulare*					✓		*inshore*					✓		*coastal inshore*
fish	golden trevally	*Gnathanodon speciosus*			✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
fish	shark mackerel	*Grammatorcynus bicarinatus*					✓		*inshore*					✓		*coastal inshore*

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fish	dogtooth tuna	*Gymnosarda unicolor*						✓	*offshore*						✓	*offshore*
fish	weed whiting	*Haletta semifasciata*			✓	✓			*estuary coastal*			✓	✓			*estuary coastal*
fish	ocean perch	*Helicolenus percoides*					✓		*inshore*					✓	✓	*coastal offshore*
fish	Castelnau's herring	*Herklotsichthys castelnaui*		✓	✓				*estuary*		✓	✓	✓			*estuary coastal*
fish	orange roughy	*Hoplostethus atlanticus*						✓	*offshore*						✓	*offshore*
fish	blue-eye trevalla	*Hyperoglyphe antarctica*						✓	*offshore*						✓	*offshore*
fish	eastern sea garfish	*Hyporhamphus australis*			✓	✓			*estuary coastal*			✓	✓			*estuary coastal*
fish	southern sea garfish	*Hyporhamphus melanochir*			✓	✓			*estuary coastal*			✓	✓			*estuary coastal*
fish	bar cod	*Hyporthodus ergastularius*					✓	✓	*offshore*					✓	✓	*coastal offshore*
fish	black marlin	*Istiompax indica*					✓	✓	*offshore*					✓	✓	*coastal offshore*
fish	sailfish	*Istiophorus platypterus*					✓		*inshore*					✓	✓	*coastal offshore*
fish	striped marlin	*Kajikia audax*						✓	*offshore*						✓	*offshore*
fish	skipjack tuna	*Katsuwonus pelamis*						✓	*offshore*						✓	*offshore*
	Silver drummer	*Kyphosus sydneyanus*				✓							✓			

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fish	barramundi	*Lates calcarifer*	✓	✓	✓				*fresh estuary*	✓	✓	✓	✓			*fresh coastal*
fish	striped trumpeter	*Latris lineata*				✓	✓		*coastal*				✓	✓		*coastal inshore*
	Blue-spotted parrotfish	*Leptoscarus vaigiensis*														
fish	blue-spotted emperor	*Lethrinus choerorynchus*			✓	✓			*estuary coastal*					✓		*coastal inshore*
fish	grass emperor	*Lethrinus laticaudis*			✓	✓			*estuary coastal*					✓		*coastal inshore*
fish	red-spot emperor	*Lethrinus lentjan*			✓	✓			*estuary coastal*					✓		*coastal inshore*
fish	red-throat emperor	*Lethrinus miniatus*					✓		*inshore*					✓		*coastal inshore*
fish	spangled emperor	*Lethrinus nebulosus*			✓	✓			*estuary coastal*					✓		*coastal inshore*
fish	longnose emperor	*Lethrinus olivaceus*					✓		*inshore*					✓		*coastal inshore*
	Flat tailed mullet	*Liza argentea*			✓							✓				
fish	tripletail	*Lobotes surinamensis*					✓		*inshore*			✓	✓	✓		*estuary inshore*
fish	mangrove jack	*Lutjanus argentimaculatus*	✓	✓	✓				*fresh estuary*				✓	✓		*coastal inshore*

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fish	red snapper	*Lutjanus erythropterus*				✓	✓		*coastal*				✓	✓		*coastal inshore*
fish	dory snapper	*Lutjanus fulviflamma*			✓	✓			*estuary coastal*				✓	✓		*coastal inshore*
fish	fingermark snapper	*Lutjanus johnii*			✓	✓	✓		*estuary inshore*			✓	✓	✓		*estuary inshore*
fish	saddle-tail snapper	*Lutjanus malabaricus*				✓	✓		*coastal*				✓	✓		*coastal inshore*
fish	Maori snapper	*Lutjanus rivulatus*			✓	✓			*estuary coastal*				✓	✓		*coastal inshore*
fish	Moses perch	*Lutjanus russellii*		✓	✓	✓			*estuary coastal*				✓	✓		*coastal inshore*
fish	red emperor	*Lutjanus sebae*				✓	✓		*coastal*				✓	✓		*coastal inshore*
fish	estuary perch	*Macquaria colonorum*	✓	✓	✓				*fresh estuary*	✓	✓	✓				*fresh coastal*
fish	Australian bass	*Macquaria novemaculeata*	✓	✓					*fresh*	✓	✓	✓				*fresh coastal*
fish	blue grenadier	*Macruronus novaezelandiae*			✓	✓	✓		*estuary inshore*						✓	*offshore*
	black marlin	*Makaira indica*					✓	✓						✓	✓	
fish	blue marlin	*Makaira mazara*						✓	*offshore*						✓	*offshore*
fish	tarpon	*Megalops cyprinoides*	✓	✓	✓				*fresh estuary*			✓	✓			*estuary coastal*

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fish	horseshoe leatherjacket	*Meuschenia hippocrepis*				✓	✓		*coastal*				✓	✓		*coastal inshore*
fish	fan-bellied leatherjacket	*Monacanthus chinensis*			✓	✓			*estuary coastal*			✓	✓			*estuary coastal*
fish	sea mullet	*Mugil cephalus*	✓	✓	✓				*fresh estuary*		✓	✓	✓			*estuary coastal*
	Sand mullet	*Myxus elongatus*			✓							✓				
fish	chinaman-leatherjacket	*Nelusetta ayraudi*				✓	✓		*coastal*					✓	✓	*coastal offshore*
fish	grey morwong	*Nemadactylus douglasii*					✓		*inshore*					✓		*coastal inshore*
fish	jackass morwong	*Nemadactylus macropterus*					✓		*inshore*					✓		*coastal inshore*
fish	blue morwong	*Nemadactylus valenciennesi*					✓		*inshore*					✓		*coastal inshore*
	Blue salmon catfish	*Neoarius graeffei*			✓	✓						✓	✓			
fish	spiky oreo	*Neocyttus rhomboidalis*						✓	*offshore*						✓	*offshore*
	Toothy flathead	*Neoplatycephalus aurimaculatus*														
fish	deepwater flathead	*Neoplatycephalus conatus*					✓	✓	*offshore*					✓	✓	*coastal offshore*

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fish	tiger flathead	*Neoplatycephalus richardsoni*					✓		*inshore*					✓	✓	*coastal offshore*
fish	bluethroat wrasse	*Notolabrus tetricus*				✓			*coastal*				✓	✓		*coastal inshore*
	Southern maori wrasse	*Ophthalmolepis lineolata*				✓							✓			
fish	yellowspotted boarfish	*Paristiopterus gallipavo*					✓	✓	*offshore*					✓	✓	*coastal offshore*
fish	giant boarfish	*Paristiopterus labiosus*					✓	✓	*offshore*					✓	✓	*coastal offshore*
fish	longsnout boarfish	*Pentaceropsis recurvirostris*					✓		*inshore*					✓		*coastal inshore*
	Hump-headed batfish	*Platax batavianus*														
	Narrow-banded batfish	*Platax orbicularis*														
	Round-faced batfish	*Platax teira*														
fish	sand flatheadf	*Platycephalus bassensis*				✓	✓		*coastal*				✓	✓		*coastal inshore*
	Blue-spotted flathead	*Platycephalus caeruleopunctatus*														
fish	bar-tailed flathead	*Platycephalus endrachtensis*		✓	✓				*estuary*			✓	✓			*estuary coastal*
fish	dusky flathead	*Platycephalus fuscus*		✓	✓				*estuary*			✓	✓			*estuary coastal*

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	Southern blue-spotted (Yank) flatheard	*Platycephalus speculator*											✓			
	Netted sweetlip	*Plectorhinchus flavomaculatus*				✓	✓						✓	✓		
	Brown sweetlip	*Plectorhinchus gibbosus*			✓								✓	✓		
fish	bluespot coral trout	*Plectropomus laevis*					✓		*inshore*					✓		*coastal inshore*
fish	common coral trout	*Plectropomus leopardus*					✓		*inshore*					✓		*coastal inshore*
fish	bar-cheeked coral trout	*Plectropomus maculatus*					✓		*inshore*					✓		*coastal inshore*
fish	king threadfin salmon	*Polydactylus sheridain*		✓	✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
fish	bass groper	*Polyprion moeone*					✓	✓	*offshore*					✓	✓	*coastal offshore*
fish	hapuku	*Polyprion oxygeneios*					✓	✓	*offshore*					✓	✓	*coastal offshore*
fish	golden grunter	*Pomadasys argenteus*			✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
fish	spotted javelinfish	*Pomadasys kaakan*			✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
fish	tailor	*Pomatomus saltrix*			✓	✓			*estuary coastal*				✓	✓		*coastal inshore*

Group	Common name	*Species*	Juveniles: freshwater	Juveniles: transitional wetlands	Juveniles: estuary	Juv: coasts, bays, headlands. beaches	Juv: inshore waters (incl. coral reefs)	Juveniles: offshore waters	***Nursery group***	Adults: freshwater	Adults: transitional wetlands	Adults: estuary	Adults: coasts, bays, headlands, beaches	Adults: inshore waters (incl. coral reefs)	Adults: offshore waters	***Adult group***
fish	sixplate sawtail	*Prionurus microlepidotus*			✓	✓			*estuary coastal*				✓	✓		*coastal inshore*
	Rosy snapper	*Pristipomoides filamentosus*												✓	✓	
fish	gold band snapper	*Pristipomoides multidens*						✓	*offshore*						✓	*offshore*
fish	sharptoothed snapper	*Pristipomoides typus*						✓	*offshore*						✓	*offshore*
fish	black jewfish	*Protonibea diacanthus*			✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
fish	silver trevally	*Pseudocaranx dentex*			✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
fish	smooth oreo	*Pseudocyttus maculatus*						✓	*offshore*						✓	*offshore*
fish	southern bastard codling	*Pseudophycis barbata*					✓		*inshore*					✓		*coastal inshore*
fish	small-toothed flounder	*Pseudorhombus jenynsii*			✓	✓			*estuary coastal*			✓	✓			*estuary coastal*
fish	cobia	*Rachycentron canadum*				✓	✓		*coastal*				✓	✓	✓	*coastal offshore*
fish	gemfish	*Rexea solandri*						✓	*offshore*						✓	*offshore*
fish	tarwhine	*Rhabdosargus sarba*		✓					*estuary*			✓	✓	✓		*estuary inshore*
fish	Australian bonito	*Sarda australis*				✓	✓		*coastal*				✓	✓		*coastal inshore*
	Oriental bonito	*Sarda orientalis*				✓	✓						✓	✓		

Group	Common name	*Species*	Juveniles: freshwater	Juveniles: transitional wetlands	Juveniles: estuary	Juv: coasts, bays, headlands. beaches	Juv: inshore waters (incl. coral reefs)	Juveniles: offshore waters	***Nursery group***	Adults: freshwater	Adults: transitional wetlands	Adults: estuary	Adults: coasts, bays, headlands, beaches	Adults: inshore waters (incl. coral reefs)	Adults: offshore waters	***Adult group***
fish	pilchard	*Sardinops sagax*			✓	✓	✓		*estuary inshore*				✓	✓		*coastal inshore*
fish	blue (slimey) mackerel	*Scomber australasicus*			✓	✓	✓		*estuary inshore*				✓	✓		*coastal inshore*
fish	queenfish	*Scomberoides commersonnianus*			✓	✓	✓		*estuary inshore*			✓	✓	✓		*estuary inshore*
fish	barred quennfish	*Scomberoides tala*			✓	✓	✓		*estuary inshore*			✓	✓	✓		*estuary inshore*
fish	narrow-barredspanish mackerel	*Scomberomorus commerson*			✓	✓	✓		*estuary inshore*			✓	✓	✓		*estuary inshore*
fish	Australian spotted mackerel	*Scomberomorus munroi*			✓	✓	✓		*estuary inshore*			✓	✓	✓		*estuary inshore*
fish	Queensland school mackerel	*Scomberomorus queenslandicus*			✓	✓	✓		*estuary inshore*			✓	✓	✓		*estuary inshore*
fish	broad-barred mackerel	*Scomberomorus semifasciatus*			✓	✓	✓		*estuary inshore*			✓	✓	✓		*estuary inshore*
fish	red rock cod	*Scorpaena cardinalis*				✓	✓		*coastal*				✓	✓		*coastal inshore*
fish	sea sweep	*Scorpis aequipinnis*					✓	✓	*offshore*					✓	✓	*coastal offshore*
fish	banded sweep	*Scorpis georgiana*				✓	✓		*coastal*				✓	✓		*coastal inshore*

Group	Common name	*Species*	Juveniles: freshwater	Juveniles: transitional wetlands	Juveniles: estuary	Juv: coasts, bays, headlands. beaches	Juv: inshore waters (incl. coral reefs)	Juveniles: offshore waters	***Nursery group***	Adults: freshwater	Adults: transitional wetlands	Adults: estuary	Adults: coasts, bays, headlands, beaches	Adults: inshore waters (incl. coral reefs)	Adults: offshore waters	***Adult group***
fish	silver sweep	*Scorpis lineolata*			✓	✓			*estuary coastal*				✓			*coastal inshore*
fish	amberjack	*Seriola dumerili*				✓	✓	✓	*coastal*				✓	✓		*coastal inshore*
fish	samsonfish	*Seriola hippos*				✓	✓	✓	*coastal*				✓	✓		*coastal inshore*
fish	yellowtail kingfish	*Seriola lalandi*			✓	✓	✓	✓	*coastal*			✓	✓	✓		*estuary inshore*
fish	blue warehou	*Seriolella brama*						✓	*offshore*						✓	*offshore*
fish	spotted warehou	*Seriolella punctata*						✓	*offshore*						✓	*offshore*
fish	King Georg whiting	*Sillaginodes punctata*			✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
fish	goldenline whiting	*Sillago analis*			✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
fish	western school whiting	*Sillago bassensis*			✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
fish	sand whiting	*Sillago ciliata*			✓	✓			*estuary coastal*			✓	✓			*estuary coastal*
fish	eastern school whiting	*Sillago flindersi*			✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
fish	trumpeter whiting	*Sillago maculata*			✓	✓			*estuary coastal*			✓	✓			*estuary coastal*

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fish	yellowfin whiting	*Sillago schomburgkii*			✓	✓			*estuary coastal*			✓	✓			*estuary coastal*
fish	banded school whiting	*Sillago vittata*			✓	✓			*estuary coastal*			✓	✓	✓		*estuary inshore*
fish	great barracuda	*Sphyraena barracuda*		✓	✓	✓			*estuary coastal*			✓	✓	✓	✓	*estuary inshore*
fish	pickhandle barracuda	*Sphyraena jello*			✓	✓	✓		*estuary inshore*			✓	✓	✓		*estuary inshore*
fish	Australian barracuda	*Sphyraena novaehollandiae*			✓	✓			*estuary coastal*			✓	✓			*estuary coastal*
fish	sawtooth barracuda	*Sphyraena putnamae*			✓	✓	✓		*estuary inshore*			✓	✓	✓		*estuary inshore*
fish	blackfin barracuda	*Sphyraena qenie*			✓	✓	✓		*estuary inshore*			✓	✓	✓		*estuary inshore*
	chinaman fish	*Symphorus nematophorus*					✓							✓		
fish	yellowfin tuna	*Thunnus albacares*						✓	*offshore*						✓	*offshore*
	albacore	*Thunnus alalunga*												✓	✓	
fish	southern bluefin tuna	*Thunnus maccoyii*						✓	*offshore*						✓	*offshore*
fish	bigeye tuna	*Thunnus obesus*						✓	*offshore*						✓	*offshore*
fish	longtail tuna	*Thunnus tonggol*				✓	✓		*coastal*				✓	✓		*coastal inshore*

Group	Common name	*Species*	Juveniles: freshwater	Juveniles: transitional wetlands	Juveniles: estuary	Juv: coasts, bays, headlands. beaches	Juv: inshore waters (incl. coral reefs)	Juveniles: offshore waters	***Nursery group***	Adults: freshwater	Adults: transitional wetlands	Adults: estuary	Adults: coasts, bays, headlands, beaches	Adults: inshore waters (incl. coral reefs)	Adults: offshore waters	***Adult group***
fish	barracouta	*Thyrsites atun*			✓	✓			*estuary* *coastal*				✓	✓	✓	*coastal* *offshore*
fish	permit	*Trachinotus blochii*			✓	✓			*estuary* *coastal*			✓	✓	✓		*estuary* *inshore*
fish	common dart	*Trachinotus botla*			✓	✓			*estuary* *coastal*			✓	✓	✓		*estuary* *inshore*
fish	swallowtail dart	*Trachinotus coppingeri*			✓	✓			*estuary* *coastal*			✓	✓			*estuary* *coastal*
fish	jack mackerel	*Trachurus declivis*			✓	✓			*estuary* *coastal*			✓	✓	✓		*estuary* *inshore*
fish	yellowtail scad	*Trachurus novaezelandiae*			✓	✓			*estuary* *coastal*			✓	✓			*estuary* *coastal*
fish	hairtail	*Trichiurus lepturus*			✓	✓			*estuary* *coastal*			✓	✓	✓		*estuary* *inshore*
	Crocodile longtom	*Tylosurus crocodilus*			✓							✓	✓	✓		
	Stout longtim	*Tylosurus gavialoides*			✓							✓	✓	✓		
	Black finned longtim	*Tylosurus acus melanotus*														
	Cale cale trevally	*Ulua mentalis*			✓	✓						✓	✓			
	Blue tailed mullet	*Valamugil buchanani*			✓	✓						✓	✓			
fish	broadbill swordfish	*Xiphias gladius*						✓	*offshore*						✓	*offshore*
	Shortfin batfish	*Zabidius novemaculeatus*														

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fish	mirror dory	*Zenopsis nebulosus*					✓	✓	*offshore*					✓	✓	*coastal offshore*
fish	John dory	*Zeus faber*			✓	✓	✓		*estuary inshore*			✓	✓	✓		*estuary inshore*
shark	bignose	*Carcharhinus altimus*					✓	✓						✓	✓	
shark	graceful	*Carcharhinus amblyhynchoides*				✓	✓						✓	✓		
shark	grey reef	*Carcharhinus amblyrhynchos*					✓	✓						✓	✓	
shark	Pigeye	*Carcharhinus amboinensis*			✓	✓	✓					✓	✓	✓		
shark	bronze whaler shark	*Carcharhinus brachyurus*				✓			*coastal*					✓	✓	*coastal offshore*
shark	spinner	*Carcharhinus brevipinna*				✓	✓						✓	✓		
shark	nervous	*Carcharhinus cautus*				✓	✓						✓	✓		
shark	whitecheek	*Carcharhinus dussumieri*				✓	✓						✓	✓		
shark	Creek	*Carcharhinus fitzroyensis*				✓	✓						✓	✓		
shark	bull shark	*Carcharhinus leucas*	✓	✓	✓				*fresh estuary*	✓	✓	✓	✓	✓		*fresh coastal*
shark	blacktip	*Carcharhinus limbatus*				✓	✓	✓					✓	✓	✓	
shark	hardnose	*Carcharhinus macloti*				✓	✓	✓					✓	✓	✓	
shark	blacktip reef	*Carcharhinus melanopterus*			✓	✓	✓					✓	✓	✓		
shark	dusky whaler shark	*Carcharhinus obscurus*				✓			*coastal*				✓	✓	✓	*coastal offshore*

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shark	sandbar shark	*Carcharhinus plumbeus*						✓					✓	✓	✓	
shark	spot-tail shark	*Carcharhinus sorrah*				✓			*coastal*				✓	✓	✓	*coastal offshore*
shark	blacktip shark	*Carcharhinus tilstoni*				✓			*coastal*				✓	✓	✓	*coastal offshore*
shark	Winghead	*Eusphyra blochii*				✓	✓						✓	✓		
shark	wiskery shark	*Furgaleus macki*					✓	✓	*offshore*					✓	✓	*coastal offshore*
shark	tiger	*Galeocerdo cuvier*				✓							✓	✓	✓	
shark	school shark	*Galeorhinus galeus*			✓	✓			*estuary coastal*					✓	✓	*offshore*
shark	fossil/snaggletooth	*Hemipristis elongata*											✓	✓	✓	
shark	Australian weasel	*Hemigaleus australiensis*											✓	✓	✓	
shark	mako shark	*Isurus oxyrinchus*						✓	*offshore*					✓	✓	*coastal offshore*
shark	Sliteye	*Loxodon macrorhinus*				✓	✓						✓	✓	✓	
shark	gummy shark	*Mustelus antarctius*			✓	✓	✓		*inshore*					✓	✓	*coastal offshore*
shark	Lemon	*Negaprion acutidens*			✓	✓						✓	✓	✓		
shark	broadnose sevengill	*Notorynchus cepedianus*				✓	✓	✓				✓	✓	✓	✓	
shark	ornate wobbegong	*Orectolobus ornatus*					✓							✓		

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shark	spotted wobbegong	*Orectolobus maculatus*				✓	✓						✓	✓		
shark	gulf wobbegong	*Orectolobus halei*				✓	✓						✓	✓		
shark	common sawshark	*Pristiophorus cirratus*					✓	✓						✓	✓	
shark	southern sawshark	*Pristiophorus nudipinnis*				✓	✓	✓					✓	✓	✓	
shark	milk	*Rhizoprionodon acutus*				✓	✓						✓	✓	✓	
shark	Australian sharpnose	*Rhizoprionodon taylori*				✓	✓						✓	✓	✓	
shark	Australian angel	*Squatina Australis*				✓	✓						✓	✓		
shark	eastern angel	*Squatina albipunctata*						✓							✓	
shark	scalloped hammerhead	*Sphyrna lewini*				✓								✓	✓	
shark	great hammerhead	*S. mokarran*				✓								✓	✓	
shark	smooth hammerhead	*S. zygaena*				✓							✓	✓	✓	
shark	whitetip reef	*Triaenodon obesus*					✓							✓		
Ray	eastern shovelnose ray	*Aptychotrema rostrata*			✓	✓						✓	✓	✓		
Ray	giant shovelnose ray	*Glaucostegus typus*			✓	✓	✓				✓	✓	✓	✓		
Ray	shark ray	*Rhina ancylostoma*				✓							✓	✓	✓	
Ray	whitespotted shovelnose	*Rhynchobatus australiae*				✓	✓						✓	✓		
Ray	smoothnose wedgefish	*Rhynchobatus laevis*				✓							✓	✓		
Ray	southern fiddler ray	*Trygonorrhina dumerilii*											✓	✓	✓	
Ray	eastern fiddler ray	*Trygonorrhina fasciata*											✓	✓	✓	
Chimaera	elephantfish	*Callorhinchus milii*			✓	✓						✓	✓	✓	✓	

Appendix 7. Project staff

James Cook University

Prof. Marcus Sheaves

Dr. Adam Barnett

Dr. Kátya Abrantes

Martha Bryans

Michael Bradley

FRDC FINAL REPORT CHECKLIST

Project Title:	Life history specific habitat utilisation of tropical fisheries species		
Principal Investigators:	Prof. Marcus Sheaves, Dr. Adam Barnett, Michael Bradley, Martha Brians, Dr. Kátya Abrantes		
Project Number:	2013/046		
Description:	In this project, we developed a detailed understanding of the sequence of habitats required by inshore Australian fisheries species at different stages of their life-histories. Information was summarised into fish-habitat matrices, an easily understandable form that can be used by different stakeholders, including management.		
Published Date:	XX/XX/XXXX (if applicable)	**Year:**	2016
ISBN:	978-0-9925222-1-6	**ISSN:**	
Key Words:	Australia, Coastal fisheries, Fish, Fisheries management, Habitat management		

Please use this checklist to self-assess your report before submitting to FRDC. Checklist should accompany the report.

	Is it included (Y/N)	**Comments**
Foreword (optional)	N	
Acknowledgments	Y	
Abbreviations	N	Not needed, not many abbreviations were used, and those that were used were well explained.
Executive Summary		
– **What the report is about**	Y	
– **Background – why project was undertaken**	Y	
– **Aims/objectives – what you wanted to achieve at the beginning**	Y	
– **Methodology – outline how you did the project**	Y	

– **Results/key findings – this should outline what you found or key results**	Y	
– **Implications for relevant stakeholders**	Y	
– **Recommendations**	Y	
Introduction	Y	
Objectives	Y	
Methodology	Y	
Results	Y	
Discussion	Y	
Conclusion	N	A general conclusion section was not included as the report was composed by five very different studies that are presented separately (one in body of report and 4 as appendices 2-5). So, conclusions for each of these studies are presented at the end of the respective chapter/Appendix.
Implications	Y	
Recommendations	Y	
Extension and Adoption	Y	
Project materials developed	Y	
Appendices	Y	