THE ROLE OF MANGROVES IN FISHERIES ENHANCEMENT

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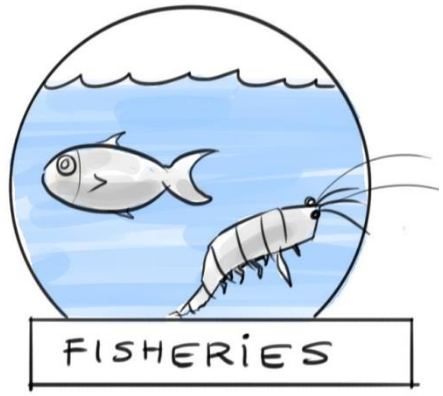

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The Nature Conservancy's **Mapping Ocean Wealth** project is a collaborative work to quantify the value of coastal and marine ecosystem services at global to local scales. On-going work under this project includes efforts to quantify and map ecosystem service values for mangrove coastal protection and carbon storage and sequestration, and work on other ecosystems such as coral reefs, seagrass, oyster and saltmarsh communities. This work is supported through a lead gift from the Lyda Hill Foundation.

The **Mangrove Capital** project aims to bring the values of mangroves to the fore and to provide the knowledge and tools necessary for the improved management of mangrove forests. The project advances the improved management and restoration of mangrove forests as an effective strategy for ensuring resilience against natural hazards and as a basis for economic prosperity in coastal areas. The project is a partnership between Wetlands International, The Nature Conservancy, Deltares, Wageningen University and several Indonesian partner organisations. This review was made possible by the Waterloo Foundation.

Cover photo by Mark Spalding

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EXECUTIVE SUMMARY

In 2011 humans caught and consumed 78.9 million tonnes of fish, crustaceans, molluscs and other species groups from the world's oceans, accounting for 16.6% of the world's animal protein intake (FAO 2012). This is projected to increase further, to over 93 million tonnes by 2030 (World Bank 2013). Global demand for fish products has increased dramatically over recent decades. Fishing is also an important livelihood, globally providing employment to 38.4 million people of whom 90% are employed in small-scale fisheries (FAO 2012). The importance of fisheries continues to rise as coastal populations are increasing, and rapidly growing economies are driving up demand for fish. While aquaculture is increasing to meet some of this demand, wild capture fisheries continue to be critically important.

This review of the scientific literature provides a deep exploration of the importance of mangroves for wild capture fisheries. While mangroves are widely recognized for their role in enhancing both small scale and commercial fisheries, they are rapidly disappearing. A fuller understanding of this ecosystem service and its value in both social and economic terms will help enhance the sustainable management of both mangroves and fisheries.

The report firstly discusses some of the ecological processes which underpin the key role of mangroves in fisheries enhancement, followed by an exploration of the different mangrove-associated fishery types. As the fisheries value of mangroves is highly site specific, the report explores the drivers and mechanisms which can help to explain for different locations how many fish a mangrove produces, how many are caught by humans, and what the fisheries value is, both in economic terms, as a food supply or through the livelihoods that they support. Decision-makers can use this information to determine where fish productivity is highest, which allows them to make adequate decisions relating to conservation and restoration actions and sustainable fishing. We conclude with management recommendations for maintaining or enhancing the value of mangroves for fisheries for the long-term.

KEY FINDINGS OF THE REPORT

- Fish productivity from mangroves will be highest where mangrove productivity is high, where there is high freshwater input from rivers and rainfall and where mangroves are in good condition.
- Fish productivity will increase with an increase in total area of mangroves, but notably also with the length of mangrove margin since generally it is the fringes of mangroves where fish populations are enhanced.
- Mangroves with greater physical complexity both in terms of patterns of channels, pools and lagoons, as well as the structure of roots which are important areas for shelter and for growth of some bivalves will enhance fisheries to a greater extent.
- Fish catch will be highest close to areas of high human population density that provide the fishers and the markets for the catch. Of course some of these mangroves close to populations are also likely to be under greater threat than those in more sparsely populated areas – they may be degraded, the waters may be polluted, or they may be over-fished and hence less productive. Where such mangroves are secured through appropriate management regimes, and where their fisheries are well managed they are likely to give greatest value. Consequently, conservation and restoration efforts in these areas close to human populations will likely give the greatest return on investment.

Fishers at Ashtamudi Lake by Nisha D'Souza

How mangroves enhance fisheries

Mangroves enhance fish production via two main mechanisms – the provision of food and of shelter. Mangroves forests are highly productive, with mean levels of primary productivity close to the average for tropical terrestrial forests. Their leaves and woody matter (detritus) form a key part of the marine food chains that supports fisheries. Decomposers of this detritus include micro-organisms such as bacteria and oomycetes, as well as some commercially important crab species. These decomposers process the leaves and woody matter into more palatable fragments for other consumers.

Mangrove productivity is further enhanced by productivity of periphyton and phytoplankton occurring on mangrove trees, in their soils and in the water column, which typically have lower rates of productivity than the trees themselves, but are nutritionally more accessible to consumers.

Moreover, mangroves often benefit from incoming nutrients from rivers and other adjacent habitats. They may also export nutrients, in the form of dissolved and particulate organic carbon, and living biomass, such as planktonic larvae and maturing fish and invertebrates.

Species of interest to the fisheries sector are found at all levels of the food chain, with detritivores such as mangrove crabs, prawns and mullet; filter feeding bivalves, planktivorous fish such as herring and anchovy species, and higher consumers such as some mud crabs and many other fish including snappers and groupers.

It is not only the high productivity of the mangroves that creates value for fisheries, but also their physical characteristics. Mangrove roots and trunks provide a structure that species such as oysters can grow on. Their roots also trap fine particles, creating soft soils ideal for molluscs and crustaceans to burrow in. Mangroves also provide shelter for many species, enabling them to avoid predation and also invest more time in feeding.

Finally, driven by the nutritional and physical benefits, many species use mangroves as nursery grounds. These include species that spend time in mangroves as juveniles before moving to offshore habitats such as coral reefs. Thus fisheries in these offshore habitats benefit from stock replacement from mangroves.

Values of mangrove-associated fisheries

Some 210 million people live in low elevation areas within 10km of mangroves and many of these benefit from mangrove-associated fisheries. The economic values of mangrove-associated fisheries vary widely, reflecting the wide range of different fisheries, economic markets, and levels of utilisation. Besides economic values, mangrove-associated fisheries provide jobs and food supplies for millions of people. In turn this may provide multiplier benefits such as political or social stability. We summarise the different types of mangrove-associated fisheries into four broad classes:

Inshore mixed species fisheries

These are mostly low-income fisheries undertaken in mangroves close to settlements. They include a broad range of fishing techniques, but many are opportunistic and fishers often return with a highly mixed catch of finfish, molluscs and crustaceans. A large proportion of the catch is for domestic consumption, but some is sold, usually in small local markets. The median value for mixed fisheries from our review was US $106/ha of mangrove/year, but variation either side of this was high.

Inshore mollusc and crustacean fisheries

Certain mollusc and crustaceans caught in mangroves generate quite high market values, and although they may still be harvested at local and small-scales, in many cases fishers are operating a targeted fishery and generating income through market sales. The most important of these are a number of crab species, oysters and other molluscs, and some harvesting of juvenile prawns for stocking of aquaculture ponds. Economic valuations are rare in the literature, but the one value we found, for a crab fishery in Micronesia, was US $423/ha of mangrove/year

Offshore commercial fisheries

These fisheries may operate many kilometres from the mangroves, but benefit from the mangroves' nursery habitat function. This distance makes it challenging to quantify the extent of this benefit. The importance of mangroves is best documented for offshore prawn fisheries, although it is rarely possible to attribute catches to specific mangrove areas. These fisheries can generate high value returns, but much of this value lies in the industrialisation of the fishery, with high volumes of catch for small numbers of fishers. We found two studies giving economic valuations, with values of 24.3 and 1394 US $/ha/year for fisheries in Indonesia and Mexico respectively.

Recreational fisheries
Mangroves are a critical habitat for a number of species that are considered prize game fish, and locations where there are healthy stocks of such fish have become favoured fishing grounds for a fishery that can be both high value and low impact. Calculations of value for these fisheries are challenging, but most efforts have included estimates of financial flows to associated beneficiaries including accommodation, transport, food and fishing guides. For example, Fishing for bonefish, permit and tarpon was worth US $56.5 million to Belize in 2007 and US $141 million to the Bahamas in 2008.

Modelling the drivers of mangrove-associated fisheries

The review work has helped to inform an understanding of the processes which drive value. The value of mangrove-associated fisheries varies greatly between different locations. To understand this variation in value we break down the benefits that mangroves provide to fisheries into three steps:

1. Potential fishable biomass

This is the biomass that would be present in a location in entirely natural condition. The productivity and availability of fish will be strongly linked to the area of mangroves. Further influence comes from the length of mangrove margin as it is primarily at the fringes of the mangrove where fish populations are enhanced. The physical complexity of the mangrove forest may also play a role, both in terms of patterns of channels, pools and lagoons, and also the structure of roots which are important areas for shelter and for growth of some bivalves. Climate, freshwater and nutrients also influence primary productivity in mangrove areas which affects fish productivity.

2. Actual fishable biomass

Most mangrove fish stocks have been influenced by humans, directly through the harvest of fish, and indirectly through changes to the environment. Even low levels of fishing will have some impact on the remaining fishable biomass, while overfishing can greatly reduce fish productivity and potential yields. Mangrove areas in many places are also compromised by pollution, while impacts to the mangroves from harvesting and clearance directly impact primary productivity and thus influence fish production.

3. Fished biomass

The amount of fish actually being caught is demand-driven, but that demand can be understood and modelled in relation to coastal population sizes, the influence of markets, of economic drivers, cultural traditions and so on. Fished biomass represents one core measure of value, but it is also a key component of other values measured in terms of money, jobs, food security and other metrics.

Recommendations for proper mangrove management

The tremendous value of mangroves for fisheries, in both social and economic terms, provides a strong incentive to secure mangroves for the long-term through proper management of both mangroves and mangrove-associated fisheries. We outline three broad classes of management which need to be considered:

Avoiding mangrove loss
Maintaining mangrove areas is almost always the most cost-efficient way of ensuring value flows over time. Critical to success are both the establishment of clear and effective regulatory frameworks, and the establishment and recognition of tenure and use rights, ideally at local or community levels. Protected areas, established for conservation purposes, already include over 25% of the world's remaining mangrove forests. However, other mechanisms – ranging from nation-wide regulations on mangrove clearance, to controls ensuring sustainability of mangrove silviculture – can also be effective. In all cases such regulations are most effective when mangrove ownership is clearly established and where communities are fully aware of the benefits they derive from adjacent mangroves.

Restoring natural mangroves
Where mangroves have been degraded or lost they can still be restored, enabling the return of ecosystem services relatively quickly. Critical to successful restoration are understanding the causes of loss in order to ensure these can be prevented in the future, and ensuring that the communities or owners of mangroves are supportive of restoration. Where these conditions are met, the main focus of restoration should be restoring growing conditions – tidal flows, freshwater inflow and sediments. These alone may be enough to allow natural mangrove recovery, but in some cases mangroves may need to be planted to commence or enhance recovery.

Managing fisheries
Fish stock management is a core principle of ensuring continued supplies and in attempting to maximise yield and/or profits. A large body of management interventions have been developed, alongside the science to inform such management.

Despite this, understanding of management of mangrove-associated fisheries *per se* remains limited. Key fisheries management tools include regulating access to the fishery, through ownership or licence; regulating fishing methods, for example to prevent wasteful bycatch or damage to the seabed; spatial controls such as the closure of certain areas permanently or seasonally to allow survival of breeding populations or key nursery areas. Market mechanisms, such as sustainable fisheries certification can provide important incentives in some fisheries to encourage and ensure implementation of such measures. Lastly, since aquaculture is a major driver of mangrove conversion, it is imperative to simultaneously work towards more sustainable aquaculture so that the fisheries enhancement function of mangroves is not jeopardized.

Education and communication are key tools in all these management interventions, to build public and political support. Many fishers are unaware of the key role mangroves may play in supporting fisheries, even those far offshore. Raising awareness can simply involve disseminating the key facts, but new ideas, including the more accurate quantification of value and explanation of key underlying drivers may greatly increase openness and enthusiasm for improvements in mangrove management.

Natural mangrove forest, Senegal. Photo by Wetlands International

INTRODUCTION

In 2011 humans caught and consumed 78.9 million tonnes of fish, crustaceans, molluscs and other species groups from the world's oceans, accounting for 16.6% of the world's animal protein intake (FAO 2012). Global demand for fish products has increased dramatically over recent decades. For example, annual per capita fish consumption doubled from 9.9 kg in the 1960s to 18.8 kg in 2011. Fishing is also an important livelihood, globally providing employment to 38.4 million people of whom 90% are employed in small-scale fisheries. The importance of fisheries continues to rise; coastal populations are increasing, and rapidly growing economies are driving up demand for fish. While aquaculture is increasing to meet some of this demand, wild capture fisheries continue to be critically important

Mangroves are forests that grow in the inter-tidal zone, at the interface of land and sea. They cover around 150,000 km² of coastline in the tropics and warm temperate regions, and are widely held to be important to both small scale and commercial fisheries. For example, 80% of all commercial or recreational species in Florida are mangrove-dependent (Hamilton and Snedaker 1984), and mangroves are crucial for 72% of the commercial fish catch in the Philippines (Paw and Chua 1991). This ecosystem service that mangroves provide has considerable economic value, in excess of US $18,000 per ha in the most productive locations (de Groot et al. 2012).

Mangroves support fisheries through two main ecological functions: their primary productivity, which forms the foundation for marine food chains that support fisheries, and their three-dimensional structure, which provides a physical environment suitable for many fishery target species. Relatively few fishery species are mangrove residents. Rather most of them are transient visitors, using mangrove forests for part of their life-cycle. Often this is during their juvenile development stage, meaning that mangroves are a nursery ground for many commercially important species.

The fisheries that mangroves support vary in scale, fishing methods and target species. They include fisheries within the mangroves themselves for mangrove-resident species such as crabs and molluscs, fisheries in mangrove channels and lagoons, and offshore fisheries for species such as penaeid prawns that use the mangroves as juveniles but move out to the continental shelf as adults. Mangrove-associated fisheries range in scale from subsistence fishing, with catches of a few hundred grams to highly commercial mechanised trawling taking hundreds of tonnes of fish or shrimp.

Fish Market in Java, Indonesia. Photo by Alexander van Oudenhoven.

In this report, we first discuss the underlying ecological factors of primary productivity and three-dimensional structure that make mangroves so crucial to fisheries in Chapter 1. Chapter 2 then discusses some of the main fishery types that are supported by mangroves. Finally, we discuss the factors that drive the variation in the importance of mangroves to fisheries in Chapter 3, and use these to highlight priority topics for mangrove conservation and restoration.

CHAPTER 1: HOW MANGROVE CHARACTERISTICS ENHANCE FISHERIES

Benefits to fisheries from mangroves come via two main mechanisms. The first is the high level of primary productivity from the mangrove trees and from other producers in the mangrove environment. This forms the basis of food chains that support a range of commercially important species. The second is the physical structure that they provide, which provides attachment points for species that need a hard substrate to grow on, as well as shelter from predation and a benign physical environment. These two mechanisms combine to make mangroves particularly effective as nursery grounds for juveniles of species that later move offshore or to adjacent habitats such as coral reefs.

In this section, we discuss these mechanisms in more depth, beginning with mangrove primary productivity and the food chains that depend on it in 1.1-1.4. In 1.5 we discuss the role that the physical structure of the mangrove plays in supporting fisheries. We then discuss the nursery function of mangroves in 1.6, and the linkages between mangroves and adjacent coastal habitats in 1.7.

1.1 Primary productivity in mangrove forests – the foundation of the fishery food web

Mangroves are highly productive ecosystems, with rates of primary productivity often rivalling those of tropical terrestrial forests. This primary productivity comes from three main sources: the mangrove trees themselves, algae growing on tree roots and on the forest floor and phytoplankton in the water column. Additionally, mangroves may receive nutrients from external sources. Each of these sources contributes to the enhanced fisheries (secondary) productivity mangroves are known to support.

1.1.1. Primary production by mangrove trees

Mangroves are highly productive ecosystems. Current estimates suggest an average above ground net primary production of 11.1 t dry weight (DW) $ha^{-1}yr^{-1}$ (Alongi 2009), which is very similar to the value of 11.9 t DW $ha^{-1}yr^{-1}$ for tropical terrestrial forests. Such average numbers mask enormous spatial variation, and actual mangrove primary productivity is determined by a range of factors, including climate, fresh water input and nutrient availability. As a general rule, productivity decreases with distance from the equator (Twilley et al. 1992), but there is high variability between sites.

Carbon captured from the atmosphere by mangrove trees is built into leaves, trunks, branches and below-ground and aerial roots. A suite of primary consumers, ranging in size from insects to monkeys and even deer and cattle, feed directly on the trees. However, with the exception of a few crab species, these are mostly terrestrial or arboreal, rather than marine. The main way in which primary production from trees supports marine secondary production is through the decomposition of fallen leaves. A recent review of mangrove litterfall found that an average of 9.6 t DW $ha^{-1}yr^{-1}$ (range 1.75 – 25.2 t DW $ha^{-1}yr^{-1}$) of leaves, propagules, twigs and branches fall to the forest floor, where it is processed by a range of consumers and decomposers (Hutchison et al. 2013).

High biomass mangroves in the Berau Delta, Kalimantan, Indonesia, a location with high rainfall and rich nutrient and freshwater supplies. Photo by Mark Spalding.

1.1.2. Primary production by periphyton

Periphyton – macroalgae and photosynthetic microorganisms growing on roots, fallen tree parts and the sediment surface – can contribute significantly to primary productivity in mangrove systems. Periphyton productivity can reach 9.9 t C $ha^{-1}yr^{-1}$ for epiphytic algae growing on pneumatophores in Florida (Dawes 1999), but is typically much lower, for example 0.1 t C $ha^{-1}yr^{-1}$ on the sediment beneath an Australian mangrove (Alongi 1994). Periphyton productivity depends on the availability of light, which in turn depends on the degree of canopy closure in the mangrove forest, and on water turbidity, which in some mangrove can reduce light intensity by 99% within 1 m (Harrison et al. 1997). Highest productivity is therefore found along creek banks and forest edges where there is more direct sunlight. Periphyton productivity will also be influenced by tidal regime, with lower productivity in areas subject to frequent desiccation, and by nutrient availability, so it may be very high in nutrient rich estuaries and may even be enhanced by nutrient pollution.

Although periphyton is likely to generate lower levels of primary productivity than the mangrove trees themselves, it is still an important component in food chains because it is easier for consumers to digest than tree detritus. Thus a number of studies have shown that algae- and phytoplankton-derived carbon may play a more important role in the diet of key commercial species than mangrove detritus (Dittel et al. 1997).

1.1.3. Primary productivity in the water column

Phytoplankton in the water column beneath mangroves forests provides a third source of primary production. Like the periphyton, planktonic production will be impacted by light availability, nutrients and tidal regime. As phytoplankton are found in the water column itself, the tidal regime and hydrology of the mangrove determines the relative importance of phytoplankton in the mangrove food web; they are more important in mangroves that are frequently or continuously flooded than in dryer mangroves where standing water is confined to channels on all but the highest tides. The tidal and hydrological regime also determines the degree to which phytoplankton is retained within the mangrove or flushed out to sea. A study in the Indus delta in Pakistan found planktonic productivity in a mangrove creek ranged from 0.5 – 3.7 t C $ha^{-1}yr^{-1}$ (Harrison et al. 1997), and similar values have been found in an Australian estuary (O'Donohue and Dennison 1997). Higher values can occur with high nutrient input, reaching 5 g C $m^{-2}d^{-1}$ downstream of a shrimp farm effluent outflow (McKinnon et al. 2002). Like benthic and epiphytic algae, phytoplankton are more palatable than mangrove detritus and are therefore important in mangrove food webs. In particular, they are grazed by zooplankton including crustacean larvae and filter feeders such as bivalves.

1.1.4. Primary production from outside the mangrove

In addition to the significant primary production by trees, periphyton and phytoplankton, mangroves also receive external organic material that is imported by the tide. The physical structure of the mangrove stems and roots slows water flow, leading to material being deposited. Tides import phytoplankton and zooplankton, including large numbers of crab larvae which are an important food source for many of the fish species found in mangroves (Rönnbäck 1999). Estuarine mangroves also receive plant material from terrestrial sources that is carried by the river and trapped in the mangroves, where it is incorporated into the detrital pathway described below.

This interconnection with other ecosystems is most clearly seen in the many places where mangroves are physically adjacent to, or even intermixed with, other coastal ecosystems, including tidal forests, salt marshes, seagrass meadows or macroalgal beds. These interconnections can be important components of a wider ecosystem, and important contributors to coastal fisheries which need to be taken into account in developing coastal management and evaluating fisheries.

1.2 The detrital pathway

While mangrove trees provide the vast majority of the primary productivity in the mangrove forest, this productivity is largely inaccessible to marine fauna. It is only when the leaves fall from the trees and enter the detrital pathway that they significantly contribute to marine food webs that ultimately support fisheries. Even having fallen from the tree, mangrove leaves are a poor food source for most animals. They have thick waxy cuticles and large quantities of lignin which is difficult to digest. Furthermore, although they are rich in sugars and other carbon compounds, they are poor sources of nitrogen and phosphorous. The leaves therefore only really begin to contribute to fisheries productivity once they have been processed by a range of decomposers. This processing begins with leaching of soluble compounds, followed by colonisation by decomposing microorganisms. The whole process takes months to years, but can be rapidly accelerated by crabs and other animals that feed on leaf litter directly, making it more accessible to other consumers (see Box 1).

1.2.1. Leaching of soluble compounds

The first step of the decomposition process is the leaching of soluble materials into the water. Within two weeks of immersion in water, 20-40% of the total carbon content of the leaf will be lost as dissolved organic carbon (DOC). The compounds lost in this way include sugars, but also tannins and other phenolic compounds. The loss of these latter two groups is important in allowing colonisation of the leaf by decomposers, as they inhibit microbial growth when present. The DOC produced by this leaching process is used as a food source by microbes in the water column, supporting their secondary productivity. The material left after this process consists of largely insoluble structural compounds within the leaf, such as cellulose and lignin.

1.2.2. Colonisation by decomposers

Once microbe-inhibiting compounds have been leached away, the remaining material is colonised by a variety of bacteria, fungi and oomycetes (water moulds). Unlike in terrestrial systems, fungi appear to play a relatively minor role in the decomposition process, with oomycetes, particularly the genus *Halophytophthora*, being the key players (Newell 1996). These microbes break down polysaccharides such as cellulose that make up the leaf structure. Lignin, found in cell walls in leaf veins and especially in woody parts of the tree, is the slowest compound to be broken down and thus contributes the least to secondary productivity and makes up a large proportion of the material that is incorporated in the soil. The microbes that colonise the leaf litter are themselves a more digestible and available source of nitrogen and phosphorus, thus making the leaf litter a more useful source of nutrition for detritivorous consumers such as small crustaceans.

1.2.3. Wood decomposition

In addition to leaf litter, woody material falls to the mangrove floor when branches fall from trees or when trees die or are blown down by storms. Like leaves, woody debris is broken down by a range of microbial decomposers, but more important are the teredinid wood-boring molluscs. Many mangrove species contain chemicals that are toxic to these wood-borers, so, as with leaves, there is an initial leaching phase before colonisation can occur. After this, colonisation occurs rapidly. Teredinids are bivalves in which the shell is specially adapted to bore into wood and which have symbiotic bacteria that break down cellulose. They turn branches and logs into a network of tunnels, consuming significant amounts of biomass directly as well as increasing the surface area for attack by microbial decomposers. Despite these specialised consumers, fallen wood remains slow to break

BOX 1: THE CRUCIAL ROLE OF CRABS IN THE DECOMPOSITION PROCESS

In many mangroves a large proportion of the leaf litter is directly consumed by crabs, particularly those in the family Sesarmidae. This dramatically accelerates the incorporation of mangrove biomass into the food chain. The acceleration happens in three main ways:

1. Shredding – as crabs feed on leaf litter they shred it into fine particles, increasing the surface area for leaching and microbial colonisation. An Australian study found that 20% of the material processed by crabs is dropped without being ingested (Camilleri 1989), but even this is shredded into fine particles.
2. Accelerated leaching – 85% of the leaf litter ingested by crabs ends up in faeces. Processing of this material in the crab gut reduces content of unpalatable tannins in faeces to < 3%, compared to 13% in freshly fallen leaves (Lee 1998). This process means that decomposing microbes can colonise the processed leaves in hours or days, rather than the weeks required without crabs.
3. Assimilation – around 12% of the leaf litter processed by crabs is assimilated as crab biomass. A range of predators then feed on these crabs, including a number of fish species that are of high importance to fisheries (Sheaves and Molony 2000). Additionally, crabs will invest a proportion of the energy assimilated in reproduction, producing large numbers of crab larvae which are an important food source to smaller predators. This "short circuits" the mangrove food chain, allowing production from mangrove trees to reach commercially important species without passing through the detrital pathway.

Estimates for the amount of litter consumed by crabs vary. In many mangroves, crabs play a major role: one Australian study found that 70% of *Bruguiera* leaves and 88% of *Ceriops* leaves were taken down crab burrows in an Australian mangrove, and those left on the surface were eaten by crabs where they fell (Robertson and Daniel 1989b). Similar results have been found in Brazil, where the crab *Ucides cordatus* was found to consume 84.2% of the total daily litterfall (Nordhaus et al. 2006).

Where crabs are less abundant, snails may play a similar role, consuming up to 42% of the total litterfall in a Kenyan mangrove (Slim et al. 1997). Similarly, other small invertebrates such as amphipods and isopods may contribute to leaf shredding. The role of macro consumers may, however, be minimal in some locations: a Florida study found no leaf consumption by crabs and only very minor grazing by snails (McIvor and Smith 1995).

down: in a study in an Australian mangrove, only 50% of the total carbon was lost from wood over 6.5 years (Robertson and Daniel 1989a).

1.3 Export of nutrients from the mangrove

Water flows from mangroves may also export nutrients, thus supporting food chains in other ecosystems. The extent and importance of this exported material varies greatly from one mangrove forest to another. Forest productivity and litterfall is a key driver determining the total amount of material available for export. The proportion of this available litter that is exported depends on geomorphological characteristics such as mangrove area and shape, rainfall and river flows, and on tidal regime including tidal range, periodicity and volume (Alongi 2009), as well as the activity of crabs and other herbivores. This combination of factors means that some mangrove sites are large net exporters whilst other may be net importers of organic material.

1.3.1. Nutrient export mechanisms

Organic matter is exported from mangroves in at least three ways. Firstly, solid material can be picked up by the flow of water and carried out of the mangrove as particulate organic carbon (POC). Secondly, soluble compounds such as sugars and tannins are leached out of leaves and carried out to sea as dissolved organic carbon (DOC). Both of these forms of transport will be most effective where tides are large and ebb-dominant (where the outgoing ebb tides has a stronger flow than the incoming flood tide), or where there is a net flow of water out to sea such as in an estuary or delta. By contrast, there will be less export of material in locations such as oceanic islands where tides are smaller and freshwater input is limited. Nevertheless, the quantity of carbon exported is often substantial, with global estimates ranging from 29 to 46 Tg C yr^{-1} (Jennerjahn and Ittekkot 2002, Alongi 2009). The higher estimate represents 11% of the total terrestrial carbon input to the oceans. It is less clear what role this exported material plays in offshore food webs. Studies in Kenya (Hemminga et al. 1994) and Florida (Lin et al. 1991) found that mangroves contribute to food webs in adjacent sea grass beds, but this influence declines rapidly with distance from the mangrove and is generally undetectable a few kilometres offshore (Kristensen et al. 2008).

The third method by which material is exported is in the form of living biomass. This living biomass may be exported at a range of trophic levels, including as phytoplankton, zooplankton, fish and crab larvae, or as biomass consumed by adult fish that move into the mangrove to hunt before moving back out to other habitats. (Sheaves and Molony 2000, Oliveira-Neto et al. 2007)

1.4 Mangrove food chains

The high level of mangrove derived primary production forms the base of a complex food web that supports a diverse mangrove fauna and numerous commercially valuable species (Figure 1). This primary production is accessed by fauna in a variety of ways – some primary production is directly grazed, but much is also accessed via decomposition and detrital pathways. Mangrove detritivores may be relatively generalist and often graze algae as well as consuming detritus; deposit feeders feed on detritus that has been incorporated into the sediment; and filter feeders and suspension feeders (including both sessile organisms and free living zooplankton) directly consume phytoplankton. Most of these groups contain species of commercial fisheries importance, but most of the high value fish species, and some important crustaceans are at the next trophic level, preying on these primary consumers.

Creek flowing through mangrove. Photo by Mark Spalding.

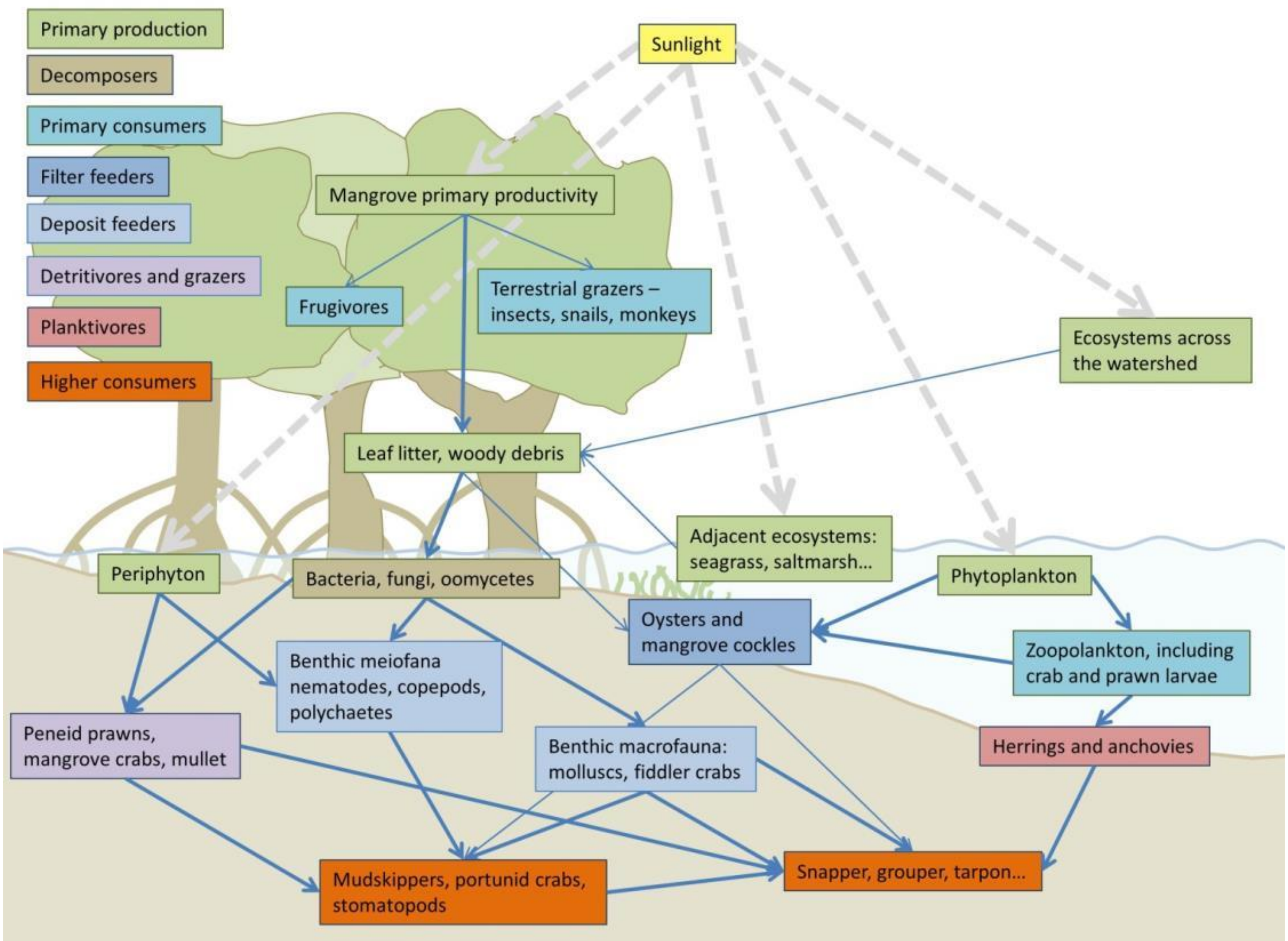

Figure 1: Simplified mangrove food web showing the broad trophic groups

1.4.1. Detritivores and grazers

Key groups: Crustaceans, gastropods, fish
Important fishery species: Penaeid prawns, and other larger species from detritivore groups such as mangrove crabs *Ucides cordatus*, and mullet (Mugilidae)

Detrivores and grazers directly consume mangrove detritus as well as periphyton and algae from the sediment surface. Some species such as mullet are relatively non-selective in what they eat; they feed by scooping up a mix of detritus, algae and sediment, which they then grind up in their thick walled, muscular stomach, drawing out the available nutrients, with the rest passing through. Crabs and prawns, by contrast, graze on individual leaf fragments and algae from the sediment surface or periphyton. Mangrove leaves are originally rich in carbon but poor in other nutrients, but become colonised by microbial decomposers rich in nitrogen and other essential nutrients. These microbes are a crucial part of the diet of detritivores, and selective detritivores therefore preferentially eat older leaf litter rather than freshly fallen leaves (e.g. Micheli 1993).

1.4.2. Deposit feeders

Key groups: Polychaete worms, gastropods, crabs
Important fishery species: N.A.

Deposit feeders consume organic material in the sediment, typically by ingesting large quantities of sediment and extracting the edible material from it in the gut. The most obvious examples are polychaete worms which consume sediment as they burrow. Many crab species also process sediment to extract nutrients, including some of the species that primarily feed on leaves. Mangrove detritus, bacteria, benthic diatoms and algae are all consumed in this way.

Deposit-feeding fiddler crab. Photo by Mark Spalding.

1.4.3. Filter and suspension feeders

Key groups: Bivalves, planktonic crustaceans, fish, sponges, polychaete worms
Important fishery species: Oysters (*Crassostrea* spp., *Saccostrea* spp.), mangrove cockles (*Anadara* spp.), Fish in the Clupeiformes, including herrings (Clupeidae) and anchovies (Engraulidae)

Filter feeders feed on organic matter in the water column, using various methods to capture their food. Crustaceans generally use hairs on their legs or claws as their filter, while filter feeding fish use their gill rakers, swimming forward with their mouth open to pass food across them. Bivalves use cilia, microscopic beating hairs, to draw water across their gills, where suspended food is trapped in a layer of mucus and then transported to the mouth. Small planktonic filter feeders feed on phytoplankton and bacteria, whereas larger filter feeders such as fish and bivalves also consume zooplankton and mangrove detritus suspended in the water column.

1.4.4. Higher level consumers

Key groups: Fish, crustaceans, gastropods
Important fishery species: Portunid crabs e.g. *Scylla* spp., *Callinectes* spp., Fish e.g. snappers (Lutjanidae), groupers (Serranidae)

Most of the primary consumers described above are preyed upon by a broad suite of predators. Whilst many animals at lower trophic levels are mangrove residents, most predators are transient visitors. Some species use mangroves only at certain life history stages, for example snapper may live in the mangrove as juveniles before moving to coral reefs as adults. Other species live outside the mangrove but enter it at high tide to feed. The larger portunid crabs are an exception to this. Several species, notably those in the genus *Scylla*, are mangrove residents and only leave the mangrove to spawn offshore.

Mud crab Scylla sp. with newly caught fish, Queensland, Australia. Photo by Mark Spalding.

1.5 Physical characteristics of the mangrove

Alongside the high productivity of mangroves, another key feature that makes mangroves attractive to fishery target species is the physical structure they provide. Mangroves provide a solid, three-dimensional structure in the form of trunks, branches, complex aerial roots and fallen debris. The geomorphology of the mangrove sediments can also be complex, with dense networks of winding and branching drainage channels, smaller pools and larger open areas and lagoons. This structural complexity is beneficial to fish and invertebrates through the provision of attachment points, by providing shelter from predation and by reducing physical disturbances and stress.

1.5.1. Attachment points

The three-dimensional structure provided by mangrove trunks and roots provides attachment points for organisms that need a hard substrate to attach to and are therefore unable to live in the soft sediments typical of unstructured estuarine habitats. These include macroalgae which provide additional primary productivity and a food source for animals. Of more direct interest to fisheries though, are several species of mangrove oyster. In the Atlantic, these include *Crassostrea rhizophorae* from the Americas, *Crassostrea tulipa* from West Africa (Vakily et al. 2012) and *Crassostrea gasar*, found on both sides of the Atlantic (Lapègue et al. 2002). In the Indo-Pacific these are replaced primarily by species of the genus *Saccostrea*, including *Saccostrea cucullata* (Jana et al. 2013), and *Saccostrea echinata*. Oysters are harvested directly from mangrove roots, and in many locations are also cultured by collecting spat (oyster larvae) on suitable surfaces and growing these on wooden structures or ropes suspended from rafts. Other species that are harvested directly from mangrove roots include wood-boring bivalves of the genus *Teredo*, which are a delicacy called "tamilok" in the Philippines and are also eaten in Brazil, as well as many species of snail that are harvested by local subsistence fisheries.

Oysters on Rhizophora roots in Fiji. Photo by Mark Spalding.

1.5.2. Shelter from predators

The structural complexity of the mangrove environment also provides shelter from predators. Roots and trunks reduce prey visibility and impede access of large predators into shallow areas. Shade from the mangrove canopy and turbid water, a characteristic of many mangroves, also make prey harder for predators to detect. This reduces predation pressure on juvenile fish and prawns, increasing the number that survive and can be recruited into the fishery. This is supported by studies which find higher numbers of fish near to mangrove shelter than in clear habitats (Sheaves 1996), or higher fish abundance deeper into the mangrove where larger carnivorous fish were not found (Rönnbäck et al. 1999). The latter study also found more fish amongst *Avicennia* pneumatophores than amongst *Rhizophora* prop roots, suggesting that the type of structure may also be important. Experimental studies also show that fish and prawns spend more time near shelter in the presence of predators, and that tethered fish are more likely to be eaten on a mudflat than in mangrove or seagrass habitats (Laegdsgaard and Johnson 2001, Meager et al. 2005). The presence of structure may also increase growth rate, as the reduced predation pressure means that potential prey are able to spend more time feeding and less time avoiding predators.

1.5.3. Physical environment

Finally, the structure provided by the mangrove generates a relatively benign physical environment for juvenile fish and prawns, with low current speeds, soft sediment, shallow water and reduced wave action. The mangrove vegetation creates friction with the water, slowing the rate at which it flows. This means that water is retained after the tide has fallen. This phenomenon is known as lateral trapping, and it increases the retention of planktonic larvae of fish and invertebrates that are imported from outside the mangrove. This gives these larvae an opportunity to settle in the mangrove environment, which increases fish and invertebrate populations, as well as providing a food source for small predators already living in the mangroves. Additionally, the mangrove trees provide shade. This regulates water temperatures, reducing stress on juvenile organisms, and also further reduces the risk of predation by making prey less visible due to lower light availability.

The slowing of the water flow by this lateral trapping effect also causes the deposition of fine sediment, creating a soft muddy floor beneath the mangrove trees. This substrate makes it easy for prawns to bury themselves and for crabs and other invertebrates to excavate burrows, providing an additional means of shelter from predators (Rönnbäck et al. 1999). The deposition of sediment creates areas of shallow water around the mangroves trees, interspersed with a network of deeper channels, providing further protection from predators for juvenile fish and prawns. The vegetation also absorbs wave energy, rapidly reducing wave heights as they pass through the mangroves (Mazda et al. 2006), which may also be an important factor for some juvenile fish and invertebrate species.

1.6 Mangroves as nursery grounds

One of the most important and widely recognized ways in which mangroves support fisheries is by providing a "nursery ground" where juvenile fishery species can grow to a size where they are less prone to predation and therefore have higher survival. Species that use mangroves as nursery grounds often move out of the mangrove as adults, perhaps to coral reefs, other offshore habitats or even freshwater rivers. Nursery grounds can be defined as habitats that produce more recruits to the adult population per unit area than other habitats in which juveniles are found (Beck et al. 2001). This is dependent on a number of factors:

- **Accessibility:** The nursery ground must be accessible to settling larvae or juveniles. While many species are likely to be able to actively select and settle amongst mangroves, such settlement may also be enhanced by the lateral trapping effect of mangroves which leads to their holding back and slowing water flows (Alongi, 2009).

- **Survival:** The complex structure of mangrove ecosystems provides shelter from predation meaning that juvenile survival rates are likely to be higher than those in unstructured estuarine environments.
- **Growth:** Growth rates, and therefore the length of time to maturity, are strongly influenced by food supply. Mangroves are highly productive, providing an abundant food supply for juveniles and facilitating high growth rates. The shelter from predation may also allow juveniles to spend less time seeking shelter and more time feeding, further increasing growth rate.

Among the many species of fishery importance which use mangroves in this nursery function are many species of penaeid prawns, but also finfish species including snappers, grunts, drums, emperors, and whiting.

1.7 Linkages with adjacent ecosystems

Most marine ecosystems are open systems with considerable fluxes of both organisms and non-living components with adjacent coastal or riverine waters. Mangroves are no exception as demonstrated by their widespread utilisation as a nursery habitat for many species (Manson et al. 2005) that remain outside of mangroves as adults, and the noted import or export of primary productivity from mangrove systems (Jennerjahn and Ittekkot 2002). The magnitude of these fluxes is challenging to quantify both at the species and the ecosystem level and is likely highly variable between sites.

1.7.1. Ecological linkages

Many offshore species are found in mangroves during part of their life cycle, most commonly as juveniles. Indeed, juveniles of some species of penaeid prawn are found almost exclusively in mangroves. Many fish species are also found in mangroves as juveniles, and studies have demonstrated the movement of juveniles from mangroves to coral reefs and other offshore habitats (Kimirei et al. 2013).

Commercially valuable penaeid prawns are found in high abundance in mangrove systems as juveniles (Rönnbäck et al. 1999, Vance et al. 2002). Penaeid prawns spawn offshore, but their planktonic larvae drift and ultimately settle in estuarine waters where they spend a few months to a year before once again migrating off shore (Potter et al. 1986). Mangroves are believed to be a particularly important part of this estuarine stage, providing them with both abundant detrital food resources and a refuge from predation. The degree to which these services result in increased off shore abundances, and in particular in offshore catches, is still debated. There are numerous studies that show a positive correlation between catches and mangrove forest area (e.g. Martosubroto and Naamin 1977, Paw and Chua 1991), but it is difficult to untangle the influence of mangroves from that of other habitats within the broader estuarine system (Manson et al. 2005), or other factors such as freshwater input. Estimation is further complicated as prawns may be caught many kilometres from their nurseries.

Mangroves also have high abundances of juveniles of many fish species, and their presence has been documented to increase the abundance of fish in adjacent habitats such as coral reefs and seagrasses (e.g. Mumby et al. 2004, Jelbart et al. 2007). In some cases fish that commonly utilise mangroves as juveniles have been found to be absent from stretches of coast with little or no mangrove (Mumby et al. 2004). The linkage between mangroves and adjacent habitats can be locally strong. In Tanzania, for example, 99% of Dory snapper, *Lutjanus fulviflamma*, caught on coral reefs had lived in mangroves as juveniles (Kimirei et al. 2013).

Aside from mangroves, structured marine habitats such as coral reefs and seagrass beds are themselves believed to be important nursery grounds for some fish species (e.g. Nagelkerken et al. 2000, Verweij et al. 2008). The linkage between these habitats is therefore not always straightforward. The benefits of having habitats adjacent to one another may be additive (e.g. Nagelkerken et al. 2001), or the habitats may provide redundancy, with one being used if the other is lost (e.g. Bologna 2014). There are numerous studies that find movement of fish between coastal habitat types at different life stages (e.g. Cocheret de la Morinière et al. 2003, Lugendo et al. 2005). This highlights the potential importance of habitat linkages in enhancing fish productivity, while also making it challenging to isolate the role of mangroves in supporting fisheries in such mixed habitat systems.

1.7.2. Nutritional linkages – import and export

Mangroves export considerable volumes of organic carbon into adjacent waters (see 3.1). As much as 11% of the total terrestrial carbon exported to marine ecosystems may be mangrove-derived (Jennerjahn and Ittekkot 2002). This exported material plays a role in food chains in adjacent seagrass and coral reef habitats, although this effect appears to be very localised (Nagelkerken et al. 2008; also see 3.1). Additionally, not all mangroves are net nutrient exporters. Many benefit from allochthonous nutrient and mineral inputs either from terrestrial and riverine sources, or indeed from marine transport.

1.7.3. Environmental modification

Mangroves benefit adjacent habitats such as coral reefs and seagrasses which are also crucial habitats for many fish species and therefore of great importance to fisheries. Both habitats are vulnerable to the effects of sediment carried out to sea by rivers. Seagrasses are benthic plants, which require clear water through which light can penetrate for photosynthesis. Corals also gain much of their energy from the photosynthesis of symbiotic algae called zooxanthellae, and are vulnerable to physical smothering by sediment. Mangroves can act like a sieve for this sediment, with the network of pneumatophores, aerial roots and trunks slowing water flow and causing the deposition of much of this sediment, preventing it from reaching other habitats. Estimates for the proportion of sediment trapped by mangroves range from 15-40% (Golbuu et al. 2003, Victor et al. 2006). In some settings, mangroves also remove nutrients from the water, thus reducing algal growth which can compete with corals for light on reefs.

Mangroves and seagrass in close proximity, Cuba. Photo by Mark Spalding.

CHAPTER 2: MANGROVE-ASSOCIATED FISHERIES

Much has been written about the value of mangroves for fisheries, and a key part of the present work has been to understand and to attempt to quantify this value. It is particularly important that such values are not simply seen as one-dimensional economic statistics. Mangrove values for fisheries need to be viewed in a host of different contexts. For example, inshore fisheries are more valuable as a protein source in coastal communities where there is no agriculture, or where poverty prevents the purchase of other protein. In terms of livelihoods, low-value fisheries may provide much higher employment than high-input, high value shrimp aquaculture which employs few or no people from local communities. Even monetary values need to be seen as multi-dimensional, depending on which sectors of society catch, prepare or market the catch, or how the spending from recreational fishing is distributed within local communities.

Coastal areas have high population densities and some of the fastest population growth rates on the planet. Some 210 million people currently live in low elevation areas within 10 km of mangrove habitats (TNC statistics). All but the most inaccessible or strictly protected mangroves will host fisheries of some sort, ranging from individuals collecting crabs and bivalves to large scale mechanized trawling or high value recreational fisheries.

Fisheries use different parts of the mangrove habitat. Molluscs and crabs can be collected amongst the trees themselves, whilst finfish can be caught in mangrove channels, estuaries, mangrove-fringed lagoons and "flats". Species such as penaeid prawns that only use mangroves for a part of their lifecycle may be caught many miles offshore from the mangrove itself.

Numerous fishing methods are employed depending on target species, cultural traditions, and on the resources available to individual fishers. These range from hand-harvesting by individuals operating on foot, to large fixed traps in mangrove channels, to complex gears operated from large vessels. Appendix 1 provides a detailed listing of the most widely used mangrove fishing methods.

In this section we firstly consider the valuation of mangrove-associated fisheries, describing previous work and summarising the methods used in this project to expand and enhance this work. We then go on to describe a number of mangrove-associated fisheries following four broad categories:

1. Inshore mixed species fisheries
2. Inshore mollusc and crustacean fisheries
3. Offshore commercial fisheries
4. Recreational fisheries

While these categories are clearly overlapping they also have distinct characteristics based on the scale of the operations, the target species and the fishing gears that are typically used.

2.1 Valuing fisheries

That mangrove-associated fisheries are of considerable value is widely accepted, and numerous studies have detailed particular values in locations around the world (see Tables 1-5). Despite this, valuing mangrove-associated fisheries is challenging, particularly at regional or global scales.

Field assessments provide the most reliable estimates of mangrove-associated fishery values (in a given location), but the quality and usefulness of such assessments is variable. Many are based on catch-at-port, which is difficult to relate back to specific mangrove areas. Studies also use highly variable approaches: while some cover all harvest from entire coastal communities, others focus on sub-sections of the fisher communities. Likewise values are reported over variable time-frames, from single rapid assessments though seasonal, to multi-year measures. The complexity and variability of the fisheries themselves is a further challenge and many studies focus on individual target species or specific fishing methods, therefore only capturing part of the total fisheries value. Smaller-scale fisheries are often overlooked as being of little economic value, but financial metrics may provide a poor measure of value in rural settings. Also, there are many species which rely on mangroves during parts of their life cycle but which are caught far from the mangroves and are therefore not counted as "mangrove species". One further challenge which frequently arises is incomplete description of studies, preventing any clear discernment of the breadth of the study in relation to the overall fisheries activities in the study region.

Despite these challenges a number of authors have attempted to summarise the value of mangroves to fisheries from local to global scales (Table 1). As might be expected their numbers range over several orders of magnitude. While some authors have reported global values (e.g. Rönnbäck 1999,

Reference	Location	Fishery	Average value (US $/ha/yr)	Value range (US $/ha/yr)	Notes
Rönnback (1999)	Global	All		850-16,750	
De Groot et al (2012)	Global (Mangroves and salt marshes)	All	Median: 234 Mean: 1,111	0-18,743	Figure is for food provision by all coastal wetlands, not just mangroves.
Aburto-Oropeza et al (2008)	Gulf of California	Offshore	37,500	25,000-50,000	Applies only to 5-10 m seaward fringe of mangrove forest.
Sathirathai & Barbier (2001)	Gulf of Thailand	All		21-69	Based on a production function linking mangrove loss to changes in catches.
Naylor & Drew (1998)	Kosrae, Micronesia	Fish and crabs	461		
Samonte-Tan et al (2007)	Bohol, Philippines	Fish, molluscs and echinoderms	49		
Gunawardena & Rowan (2005)	Sri Lanka	Clupeidae, Mugilidae and Penaeidae	754		
Walton et al (2006)	Western Visayas, Philippines	Within mangrove	213		
Walton et al (2006)	Western Visayas, Philippines	Estimated contribution to coastal and offshore fisheries	2,002		
Tognella-de-Rosa et al (2006)	Santa Catarina, Brazil	Crabs and molluscs within the mangrove	9,777		
This review	Global	Fish	Median: 77.3 Mean: 3114.8	0.2 – 12,305	See Table 3
This review	Global	Mixed species	Median: 213 Mean: 623.7	17.5 – 3,412	See Table 3

Table 1: Existing estimates of the value of mangroves to fisheries on global or local scales.

de Groot et al. 2012), the substantial variability in estimated value across studies suggests that such extrapolations, especially when expressed as simple averages, are highly uncertain and potentially misleading. Such global extrapolations also miss the spatial variability in mangrove-associated fishery values due to both local ecological factors, and a host of social, cultural and economic influences.

In preparing this report we have compiled the most detailed synthesis of the literature to date on valuation of mangrove-associated fisheries. From this we have begun to build an understanding of the main drivers of spatial variance in value. Here we briefly describe the work involved in that literature review. We go on to summarise our understanding of the major groups of fisheries, with tables of values from a range of field studies. In the final section, we describe our findings on the main drivers of fisheries value, and propose a simple conceptual model of how these drivers interact.

2.1.1. Literature review

Data on mangrove-associated fisheries around the world was collected using a systematic literature search. This used three sets of search terms to represent mangroves, fishery target groups and the action of fishing or harvesting (see Table 2). For a result to be returned it had to feature at least one term from each group in its title or abstract. The terms were used to search three scientific databases: ISI Web of Knowledge, Science Direct and Scopus, returning just over 4000 papers. Asterisks are used to denote wild-cards, so fisher*" would search for "fisher", "fishery" and "fisheries".

Mangrove Terms	Fish Terms	Action Terms	Results
mangrove*	cockle*, crab*, finfish, fish*, oyster*, prawn*, shrimp*	aquaculture, artisanal, capture, catch, farming, fisher*, fishing, gather*, growth, harvest, landing*, nursery, refuge, survival, trap*, valu*, yield	4044

Table 2: The final set of search terms used in the literature review.

The results were sorted by title and abstract, and around two thirds were discarded as irrelevant. The remaining 1579 were sorted into categories and those most likely to contain useful data on fishery catches and values were processed. This work is ongoing and further categories may be processed in future iterations.

Summary data from the identified papers were stored in a purpose-built database, from which the following data tables were extracted. Unless given in the paper, the catch/unit area and economic value/unit area were calculated by measuring the area of mangrove within the study area, using data from the USGS Global Distribution of Mangroves layer (Giri et al. 2011). In some cases this may produce very high or very low values/unit area if the mangrove area is very large or very small. Summary information, including estimates of the catch and value, from some of these studies is provided in Tables 3-5 below.

2.2 Mangrove-associated fisheries: summaries by fishery type

In this section, we describe and summarise the main characteristics of each fishery class. To illustrate the diversity and the potential value of mangrove-associated fisheries around the world, we also present a series of case studies for each of the broad mangrove fishery categories in appendix 2.

2.2.1. Inshore mixed species fisheries

It has been estimated that over 90% of the world's fishers are employed in small-scale subsistence and artisanal fisheries (FAO and World Fish Centre 2008), and small-scale marine fisheries land some 30 million tonnes of fish each year. Given the large populations adjacent to many mangrove areas and the occurrence of small-scale fisheries in most of the world's mangrove forests, mangrove or mangrove-associated fisheries are likely to be an important part of that catch. Mangrove-associated fisheries are particularly important in developing countries, where they provide a critical source of food and income for many who have few livelihood alternatives. Typically such fisheries use a broad range of fishing methods, and exploit a wide range of species.

Inshore mixed species fisheries include artisanal fisheries –conducted with limited equipment, on foot or from open boats, for small-scale commercial purposes – and subsistence fisheries where the catch is primarily used to feed the fisher, family members and close community, with limited market transactions. These categories have a large overlap, with artisanal fishers using part of their catch for subsistence, and many subsistence fisheries making occasional or opportunistic use of markets. In this report we have distinguished these fisheries from inshore mollusc and crustacean fisheries which, although also often artisanal, usually target specific species or groups to supply commercial markets.

Catches from inshore mixed-species fisheries are rarely recorded or reported, making it difficult to assess the volume or value of fish caught. Nevertheless, several estimates that clearly illustrate the importance of mangroves to inshore mixed fisheries are available in the literature. A study in a coastal province in Madagascar found that 87% of the adult population were employed in fisheries, with the majority of the men fishing and the women gleaning along the shoreline (Barnes-Mauthe et al. 2013). The 2756 fishers caught 5500 tonnes of fish and invertebrates in 2010, of which almost 2000 tonnes was caught in and around mangroves. Eighty-three percent of the catch was sold earning an average of about US $2200 per fisher. The rest was eaten by fishers' families and friends. Other studies show similar patterns in Thailand (Islam and Ikejima 2010) and Mozambique (de Boer et al. 2002). A summary of literature derived values for mixed species fisheries can be found in Table 3.

Mangrove fishers, Papua, Indonesia. Photo by Wetlands International.

Fishing methods used in these small-scale fisheries are highly variable spatially, culturally and by sector of society. Various types of net are common, including seine nets, gillnets, cast nets and lift nets, as well as traps such as fyke nets, pound nets and crab pots. Hooks and lines are also common for catching finfish. In Thailand, Islam and Ikejima (2010) described six distinct techniques observed: crab traps, channel traps, gill nets, catfish hooks, lift nets and hand capture. Hand-collecting is common, especially in the context of opportunistic gleaning along the shoreline or within the mangroves, a practice often dominated by women and children.

Small-scale fisheries often have lower environmental impacts than larger scale operations. Discards are generally low as species with low market value may still be eaten by the fisher and his family, while the high value species are sold. Environmental impact is also relatively low compared to techniques such as trawling.

Overfishing can still be a problem, however, because small-scale fisheries are often open access and may require little or no equipment making them an attractive option for those with no other source of income. This means that economic pressures and growing populations can increase fishing pressure leading to overfishing. This is demonstrated by declining catches in both Mozambique and Thailand (de Boer et al. 2001, Islam and Ikejima 2010).

FACT FILE: INSHORE MIXED SPECIES FISHERIES

Location: Mostly within the mangrove and close to settlements. Fishers travel on foot or by small boat, often human-powered, limiting the area that they can fish. Subsistence and artisanal fisheries are mostly found in developing countries, although indigenous populations in developed countries such as Australia may also use traditional fishing methods.

Target species: Subsistence and artisanal fisheries tend to be mixed-species. Higher value species are targeted, but they may also include species such as gastropods and small crabs that have no commercial value but are still edible.

Consumption: In some cases, the catch may be mostly consumed by the fisher and their family, but most fishers will also trade or sell part of their catch when they have a surplus. This trade will often be local, within the fisher's village, but may be to middle men or in larger markets if the fisher lives in or near a large population centre.

Methods: Hand-collecting is universal for molluscs and crabs. Crabs may also be trapped in pots. For fish, cast nets and gill nets are commonly used in channels and at the edges of the forest. In some regions, fishers build brush parks to attract fish and invertebrates (see case study in Appendix).

Table 3: Catches and economic values of small-scale mixed fisheries from studies found in our literature review. Where economic values were given in local currency, they have been converted to US $ using present-day exchange rates.

Reference	Country	Site	Mangrove area (ha)	Physical catch	Catch/unit area (kg/ha/yr)	Annual catch value	US$	US$/ha /yr
Bennett & Reynolds 1993	Malaysia	Sarawak Mangrove Forest Reserve	34126			21,100,000 US $	21,100,000	618.3
Carrasquilla -Henao et al 2013	Mexico	San Ignacio - Navachiste - Macapule lagoon system	10881	401.7 t/yr	36.9			
Christensen et al 2008	Vietnam	Dam Doi district	10766			2,700,000 US $	2,700,000	250.8

Reference	Country	Site	Mangrove area (ha)	Physical catch	Catch/unit area (kg/ha/yr)	Annual catch value	US$	US$/ha /yr
Conde 1996	Venezuala	Laguna de Tacarigua	5061	383,282 kg/yr	75.7			
de Boer et al 2001	Mozambique	South Inhaca island	243	26.2 t/yr	107.6			
de Graaf & Xuan 1998	Vietnam	Ca Mau	87053	104,000 t/yr	1194.7			
Grasso 1998	Brazil	Cananéia estuary	10405	1,379 t/yr	132.5			
Gunawardena & Rowan 2005	Sri Lanka	Rekawa Lagoon	69	25.2 t/yr	363.7			
Gunawardena & Rowan 2005	Sri Lanka	Rekawa Lagoon - Lagoon fishery	69	36 t/yr	519.5	3,750,000 Sri Lankan Rupees	28,500	411.3
Gunawardena & Rowan 2005	Sri Lanka	Rekawa Lagoon - Offshore fishery	69	92 t/yr	1327.7	6,900,000 Sri Lankan Rupees	52,440	756.8
Islam & Ikejima 2010	Thailand	Pak Phanang	7317	496.4 t/yr	67.8	551,050 US $	551,050	75.3
Janssen & Padilla 1999	Philippines	Pagbilao mangrove reserve	255			1,472 Philippine Pesos/ha	33.9	33.9
Kairo et al 2009	Kenya	Gazi Bay	492	94.6 kg/ha/yr	94.6	7,916 Kenyan Shillings/ha	95.0	0.2
Koranteng et al 2000	Ghana	Muni lagoon	2	228.8 kg/day				
Naylor & Drew 1998	Federated States of Micronesia	Kosrae	1299			170,000 US dollars	170,000	130.9
Nickerson 1999	Philippines	Lingayan Gulf	869			534,980 Philippine Pesos/ha	12,305	12,304.5
O'Garra 2012	Fiji	Navakavu traditional fishing grounds	232	139,371 kg/yr	601.8	790266 US $	790,266	3,412.3
Qin et al 2000	Hong Kong	Mai Po Marshes	630	400 kg/ha/yr	400.0	1,364,000 US $	1,364,000	2,164.1
Samonte-Tan et al 2007	Philippines	Bohol Marine Triangle	136			3,236 US dollars	3,236	23.7
Samonte-Tan et al 2007	Philippines	Bohol Marine Triangle	136			49 US $/ha	49.0	49.0
Semesi 1998	Tanzania	Bagamoyo	2501	1,369 t/yr	547.6			
Singh et al 2010	India	Bally village	22314	2,061 t/yr	92.3	110.6 million Indian Rupees	1,815,000	81.3
Singh et al 2010	India	Dulki village	19064	539.7 t/yr	28.3	28.8 million Indian Rupees	473,000	24.8
Singh et al 2010	India	Hamiltonabad	35642	744.6 t/yr	20.9	38.1 million Indian Rupees	625,000	17.5
Walton et al 2006	Philippines	Aklan River	55	294 kg/ha/yr	294.0	213 US $/ha	213.0	213.0

2.2.2. Inshore mollusc and crustacean fisheries

In addition to the mixed-species fisheries described in the previous section there is a substantial targeted fishing effort within mangrove areas that focuses on a few key species and is typically commercial, though often small-scale. These fisheries target a small number of invertebrates with relatively high market values, notably crabs and bivalve molluscs. Such fisheries will typically employ distinct harvesting techniques for the desired species, rather than more indiscriminate methods. These fisheries require markets for their catch, so where coastal populations are low and there is no easy access to markets they may be less common. Many of the target crab species spawn offshore and spend part of their life cycle as pelagic zooplankton before migrating back to the mangroves where they remain resident for the remainder of their lives and are therefore extremely mangrove-associated (e.g. Hill 1994, Oliveira-Neto et al. 2007).

FACT FILE INSHORE MOLLUSC AND CRUSTACEAN FISHERIES

Location: Mostly within the mangroves, but occasionally in estuaries or just offshore. Fishers mostly travel on foot or by small motor boat, often a long-tail boat using an adapted car or motorbike engine for power. They are limited by distance from settlements and to the larger population centres that provide markets for their catch. Widespread in many developing countries, but also economically viable in many developed countries.

Target species: Large crabs, oysters, cockles and sometimes juvenile penaeid prawns to stock adjacent aquaculture ponds.

Consumption: A key component of the catch is sold to traders or direct to markets. Some part of the catch may also be consumed by the fisher and their family, who may also consume some of the bycatch if the method used produces any. Highest value species may be transported internationally.

Methods: Catch methods are diverse and often highly specialised to each target species. Hand collecting is still common, particularly for sessile bivalves. Traps and nets are also used for some species.

2.2.2.1 Mangrove crustacean fisheries

Numerous crab species are found in mangroves, ranging from herbivores feeding on mangrove leaves to key predators. Many species are exploited by small-scale subsistence fisheries, but a few also have significant commercial value. Two examples are discussed in the case studies (Appendix 2). The other major crustacean groups linked to mangroves are the prawns, and while a large part of commercial prawn harvests are linked to offshore commercial sectors (see 11) there is also an important inshore fishery for juvenile prawns that are used to supply aquaculture. This fishery is gradually being replaced by larvae from hatcheries, but wild larvae are considered to be of better quality and have higher survival than hatchery-produced larvae so remain in high demand in many regions.

Relatively few examples of specific crab fisheries were found in our literature search, although the majority of the small-scale mixed catches include crabs. The examples found show that catches can reach thousands of tonnes per year, but are often much smaller than this (Table 4).

2.2.2.2 Mangrove bivalve fisheries

Bivalves are abundant in mangroves, where they benefit from the high primary productivity, and from the soft sediment for burrowing species and the solid structure that roots provide for species living on hard substrates. Many bivalve species are collected as part of mixed-species fisheries, but targeted fisheries also exist for a few commercially valuable species groups, notably oysters and mangrove cockles (see Appendix 2: Case studies).

Table 4: Catches and economic values of mangrove crab fisheries from studies found in our literature review. Where economic values were given in local currency, they have been converted to US $ using present-day exchange rates.

Reference	Country	Site	Mangrove area (ha)	Physical catch	Catch/unit area (kg/ha/yr)	Annual catch value	Annual value (US $)	US$/ ha/yr
Carrasquilla-Henao et al 2013	Mexico	San Ignacio - Navachiste – Macapule lagoon system	10881	2533.5 t/yr	232.8			
Dumas et al 2012	New Caledonia	Temala mangrove	640.9	18.2 t/yr	28.4			
Dumas et al 2012	New Caledonia	Voh mangroves	573.8	36 t/yr	62.7			
Dumas et al 2012	New Caledonia	Xujo mangrove	785.5	35.4 t/yr	45.1			
Lebata et al 2007	Philippines	Ibajay	70.00	4.1 kg/ha/yr	4.1			
Naylor & Drew 1998	Federated States of Micronesia	Kosrae	1299			$550,000 US	550,000	423.4

Bivalve collectors are often amongst the poorest members of society, as the open access conditions and little equipment required makes it an attractive option for those with no other sources of income available.

The literature review found a number of studies of mangrove bivalve fisheries, but these were largely focussed on the socio-economic aspects of the fishery so had little catch data (e.g. Mendonca and Machado 2010, Beitl 2011).

2.2.3. Offshore commercial fisheries

Most reports of mangrove-associated fisheries focus on fishing activities that take place within the mangroves and associated channels and lagoons, or in adjacent waters. In reality many species derive benefits from mangroves for only part of their life history, often migrating out from the mangroves as they mature. A number of publications have looked at the relationship between mangroves and coral reef fish (e.g. Kimirei et al. 2013, see also 7 above). The quantification of this relationship is very

FACT FILE OFFSHORE COMMERCIAL FISHERIES

Location: Offshore and across the continental shelf, sometimes 10s or 100s of kilometres from the mangroves. Fishers use larger boats capable of travelling long distances to the best fishing grounds. Much of the fishing process may be mechanised, for example through the use of winches to haul nets, reducing the number of crew needed to man the boat. Large boats may also have on board freezers to freeze the catch, meaning that fish caught do not have to be immediately brought to markets. This enables boats to stay at sea for longer and to fish further from port.

Target species: Highly targeted towards high value species, with lower value bycatch often discarded. The primary commercial target species of interest here are a number of penaeid prawns, many of which spend post-larval stages in estuarine and mangrove habitats before moving offshore as adults. A number of finfish species also show varying degrees of mangrove association in juvenile life-history stages, and are of considerable commercial importance, including barramundi *Lates calcarifer*, various species of snapper (Lutjanidae), mullet (Mugilidae) and sea catfish (Ariidae). In all cases the degree of dependence of these species on mangroves is less clearly defined and hence these fisheries are not considered further in this report.

Consumption: Catches are usually landed at larger ports with factory-scale processing facilities. Much of the catch may be frozen for export to other countries.

Methods: Penaeidae prawns are almost entirely fished with benthic trawls. Some high value finfish species such as barramundi are also targeted with gill nets and hook and line.

challenging and in the present work these fisheries enhancement benefits are not considered further, with the single exception of benthic shrimp species.

2.2.3.1. Offshore prawn fisheries

Commercially valuable prawns, mostly in the family Penaeidae, spend a few months as juveniles in inshore, especially mangrove, areas before migrating off shore for the remainder of their lives (see Appendix 1). The magnitude of the role that mangroves play as prawn nursery grounds is difficult to quantify, as prawns may be caught tens of kilometres from the mangroves they benefited from as juveniles. Nevertheless, numerous attempts have been made to determine the value of mangrove areas to offshore prawn fisheries. The reported values cover a range of spatial scales (Table 6). Reported values per unit are of mangrove vary widely. This is because the catch associated with a given area of mangrove varies not only with the extent of mangrove, but also by rainfall and temperature (Vance et al. 1985), and hence estuary location. Prawns are also highly dependent on estuaries in general, making it difficult to tease out the relative enhancement due to the presence of mangroves specifically (Lee 2004). Nevertheless, juvenile prawns are often found in greater abundance in mangroves than in other estuarine sites (e.g. Robertson and Duke 1987, Primavera 1998), and therefore it is likely that offshore fisheries are enhanced by mangroves.

Table 6: Catches and economic values of mangrove prawn fisheries from studies found in our literature review. Where economic values were given in local currency, they have been converted to US $ using present-day exchange rates.

Reference	Country	Site	Mangrove area (ha)	Physical catch	Catch/unit area (kg/ha/yr)	Annual catch value	Annual value (US$)	US$/ha/yr
Barbier & Strand 1998	Mexico	Terminos Lagoon	102402	14.4 t/km²/yr	144.0	$139,352 US	139,352	1393.5
Carrasquilla-Henao et al 2013	Mexico	San Ignacio – Navachiste - Macapule lagoon system	10881	1960 t/yr	180.1			
Chavez-Rosales et al 2008	Mexico	Magdalena Bay - Bay		55.4 t/yr				
Chavez-Rosales et al 2008	Mexico	Magdalena Bay - Mangrove channels		92 t/yr				
Chavez-Rosales et al 2008	Mexico	Magdalena Bay - Offshore		130.5 t/yr				
Chavez-Rosales et al 2008	Mexico	Magdalena Bay - Total	17772	277.9 t/yr	15.6			
Fouda & Ali-Muharrami 1995	Oman	Ghubbat Hashish	157	370 t/yr	2356.7			
Grasso 1998	Brazil	Cananéia estuary	10405	97 t/yr	9.3			
Gunawardena & Rowan 2005	Sri Lanka	Rekawa Lagoon	69	10.8 t/yr	155.9			
Ruitenbeek 1994	Indonesia	Bintuni Bay	249244	5500 t/yr	22.1	68.75 billion Rupiah	6,050,000	24.3
Semesi 1998	Tanzania	Bagamoyo	2502	188.1 t/yr	75.6			
Subrahmanyam 1973	India	Gautami-Godavari Estuary	17170	2100 t/yr	122.3			

2.2.4. Recreational fisheries

Recreational fishing is carried out for pleasure. In some cases it generates a small harvest, usually for personal consumption, but in other cases the catch may not even be kept. As a hobby or sport it is at least 350 years old, and is popular with millions of people worldwide. Mangrove fishing includes simple shore-based efforts, but also boat based fishing, and most popularly using rod-and line gears.

Among the highest value recreational targets are a range of fish species valued for their "fight"; the challenge of catching them, as opposed to their nutritional value. These fish species, such as tarpon (*Megalops* spp.) and bonefish (*Albula* spp.), attract recreational fishermen on holidays or daytrips. The transport, accommodation, food and guiding associated with these trips usually requires a high economic input and hence the value of recreational fisheries can be very high, and often higher than other mangrove-associated fisheries. For example, catch-and-release fishing for bonefish contributes around US$1 billion per year to Florida's economy (Ault et al. 2010). In developing countries recreational fishing can be a major part of the income from tourism, which may be the main source of income for many coastal communities. Fishing for bonefish, permit and tarpon was worth US $56.5 million to Belize in 2007 (Fedler and Hayes 2008), and US $141 million to the Bahamas in 2008 (Fedler 2010).

FACT FILE RECREATIONAL FISHERIES

Location: Recreational fisheries are mostly undertaken by boat and mostly based in the flats between and adjacent to mangroves.

Target species: Target species closely linked to mangroves include: bonefish (*Albula* spp.), tarpon (*Megalops* spp.) barramundi (*Lates calcarifer*), snook (*Centropomus* spp.), and snapper (especially mangrove snapper *Lutjanus argentimaculatus*).

Consumption: Obtaining fish as a source of food is often only a secondary goal in recreational fisheries. Indeed, many recreational fishers practice "catch and release" fishing, especially with species that are of conservation concern. When catches are retained they are generally small compared to commercial fisheries, although they can be a significant part of the catch of the most popular target species.

Methods: By far the most important fishing method used in recreational fisheries is hook and line. There is a wide range of different techniques within this, with different baits and lures based on target species, location and the preferences and experience of individual fishers. Some of the main techniques used include trolling, where a lure is towed behind a boat, lure fishing where a plastic or metal lure is retrieved through the water to mimic a small prey fish, and fly fishing where the lure is made of feathers or synthetic equivalents and is cast with the aid of a weighted line. Other less common forms of recreational fishing include bow fishing and spear fishing, which use arrows or spears to impale the fish. These may be used from the shore or a boat, or in the water whilst snorkelling or scuba diving. In some countries such as Australia the recreational fishery extends to cover other fishery targets, including crustaceans.

2.3 Drivers of mangrove fishery catch and value

In order to estimate the extent to which a given area of mangrove will benefit fisheries within and around it, it is necessary to understand the drivers of fish productivity and fishery value. As a habitat type, mangroves are highly variable. They are found across a broad range of climate types from wet tropical to desert and temperate regions. Individual mangrove areas may have anything between one and 50 of the roughly 65 mangrove species, and the trees may be anything from small shrubs to 40m tall forests. Environmental settings are also important: estuarine mangroves with abundant nutrients and fresh water input will be taller and more productive than mangroves on oceanic coral islands. Each individual mangrove forest is therefore unique, and this extensive variability makes predicting fish production a challenge. Nonetheless, there are some common factors that influence production and fishery value in all mangroves.

We have decided to focus valuation around three key sets of drivers (Figure 2). Firstly we consider the environmental drivers which can predict potential fishable biomass of a place – the likely amount of fish available for fishers under natural conditions. Secondly we consider the measures of condition which can helps us to predict actual fishable biomass in a place – mangroves, the surrounding waters and their fish-stocks are already impacted in almost all areas by human impacts and these typically reduce the amount of fish biomass available to fishers. Thirdly, a host of socio-economic factors determine the fished biomass in any place – this is a critical metric for ascertaining value, which can then be measured in many different ways

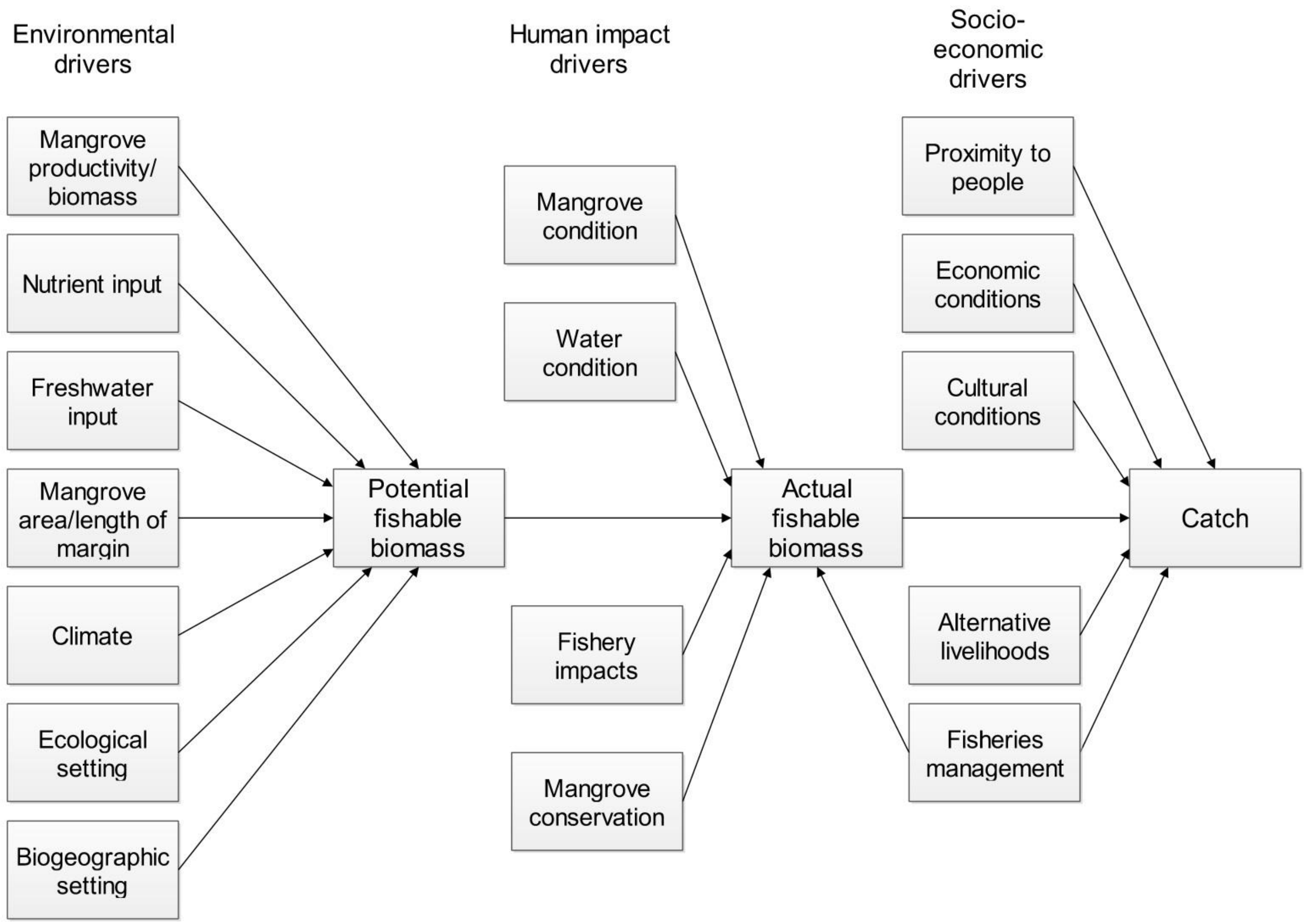

Figure 2: A conceptual model of the drivers of mangrove fishery catch and value. Environmental drivers determine the potential fishable biomass that might be present in natural conditions. The actual fishable biomass is derived by modifying the potential biomass based on human impacts on the mangrove ecosystem and fish stocks, which may be mitigated by conservation and fishery management. The catch depends on the actual fishable biomass, and the socio-economic drivers that determine fishing effort.

2.3.1. Environmental factors and potential fishable biomass

Productivity: Primary productivity, both of the mangroves themselves and of other producers on solid surfaces and in the water column, is one of the key reasons why mangroves are important to fisheries. This primary productivity provides the basis of a food web that ultimately supports species that are valuable to fisheries. High primary productivity of both mangroves and other producers will lead to increased fish production.

Nutrient supply: High levels of nutrient input will enhance mangrove growth, but perhaps as importantly the primary productivity of periphyton and phytoplankton. While it might be expected to see increased fisheries productivity associated with high nutrient levels, such a relationship would unlikely be simple and it might be expected, in extreme high nutrient settings that de-oxygenation and dead zones could lead to a dramatic fall in fish productivity.

Freshwater input: This has been positively correlated with both mangrove productivity and fish and prawn production (e.g. Vance et al. 1985, Meynecke et al. 2006). Once again this relationship will be complex: while mangroves may benefit from brackish water settings not all fishery species will survive in very low salinities. Some of the most extensive high-productivity mangroves are found in estuarine and deltaic settings, particularly in areas of year-round high flow rates. Climate can be important, with high rainfall areas also benefitting from lower salinities, while the most arid areas can suffer hyper-salinisation.

Mangrove area/length of mangrove margin: If mangroves enhance fish production and stocks, then the total area of mangrove is clearly important in determining the total numbers of fish. The shape of the mangrove block is also likely to be important. Fishery target species only penetrate a certain distance into the mangrove from the sea or from rivers. This distance is dependent on tidal height, channels in the mangrove and relief of the coastline. In larger mangrove blocks, only those fringes accessible to areas of more permanent inundation (seaward fringes, channels, lagoons, and pools) will play a significant role in enhancing fisheries, so mangrove area within a set distance of the sea or estuary may be a better indicator than total area (Aburto-Oropeza et al., 2008) as well as the length of the mangrove margin.

Climate: Climate will directly influence mangrove productivity. Temperature, rainfall and seasonality are all likely to be important. It may also influence productivity of fishery target species. In particular, the growth rate of invertebrates such as prawns and crabs are directly affected by water temperature (Staples and Heales 1991).

Biogeographic and ecological setting: Diversity of both mangroves and marine animals is not evenly distributed around the world. South-East Asia has almost 50 species of mangrove, whilst Africa and the Americas only have around 10. Even within a region there will be variation, with small islands tending to have lower diversity than large mainland forests. Physical structure of the mangrove trees varies by species, and is important in providing a large surface area for primary production; attachment points for sessile invertebrates; protection from predation; and a benign physical environment. In particular, the different aerial root structures may benefit fisheries to different extents. For example, in the Philippines, more fish were found amongst *Avicennia* pneumatophores than amongst *Rhizophora* prop roots. The same was true of juvenile prawns in the interior of the forest, but not at the seaward margins (Rönnbäck et al. 1999). Prop roots, on the other hand, are likely to provide better attachment points for bivalves such as oysters. Patterns of mangrove diversity are paralleled in a number of other marine and coastal taxa, including seagrasses, corals and fish, and it seems likely that the areas of highest mangrove diversity (from the Bay of Bengal to Northern Australia and the Solomon Islands) will also be home to the highest diversity of species of fishery interest. It remains unclear whether this will influence total productivity and biomass.

It seems likely that some combination of these drivers might be used to develop an understanding of fish productivity or standing biomass, or indeed a subset of these numbers, focusing on key targets for different fisheries. These could be represented in a conceptual model of potential fishable biomass, as shown in Figure 2.

2.3.2. Human impacts

In reality, many of the world's mangroves, and their fish-stocks, are degraded to some degree by human impacts. For the purpose of conceptualising such conditions we have distinguished three main drivers, all of which can be mitigated by conservation efforts and by management of fish stocks (included in 2.3.3).

Mangrove condition: Human influences on mangroves may also impact the extent to which they benefit fisheries. Degradation through logging, wood cutting for charcoal and pollution damage may reduce the productivity of the forest and the amount of physical structure it provides. There may also be differences between natural mangroves and mangroves that are replanted, either as forestry plantations or for restoration schemes.

Water condition: Pollution will directly influence fish and invertebrates living in the water. In some cases nutrient pollution may actually enhance productivity, but other impacts which can have negative impacts include oil pollution, anoxia driven by extremely high nutrient levels, and the occurrence of harmful aquatic blooms which can threaten marine life, but also greatly impact fisheries through human health risk impacts.

Fish-stock condition: Fisheries around the world have suffered from poor management and over-harvest, or indeed from damaging fishing practises. Mangrove-associated fisheries are similarly impacted and there are many cases where over-harvest of target stocks have been recorded and where fishers are travelling further or otherwise suffering from reduced yields. In looking at simple studies of harvest it is typically difficult or impossible to ascertain where yields are with respect to sustainable maxima.

Mangrove conservation: Around a quarter of all the world's mangrove forests are found in areas designated for the conservation of biodiversity (Spalding et al. 2010). In a few cases such protected areas may be closed to fishing, but the majority have fewer restrictions, more equivalent to fisheries management that may enhance yields and stability. In addition, such protected areas in many cases will reduce the likelihood of degradation and pollution, and so have the potential to enhance fisheries yields or value. As with fisheries management efforts, protected areas declared in policy statements or even legal documents are not always effective.

By building these condition measures onto the potential fishable biomass we can envisage a measure of actual fishable biomass, as shown in Figure 2.

2.3.3. Socio-economic factors and fished biomass

The actual, or realised, value of any resource depends not only on its availability, but on its utilisation and on the many factors which influence demand. In some cases those demands may also be the drivers of declines in condition, but this is not always the case, demand can also be regulated to prevent such declines.

Proximity to people: The presence of people within the vicinity of mangroves is a key determinant of the demand for fish. Demand might be expected to show some correlation overall coastal populations numbers, but this will also influence the type of fishing, with small-scale mixed species fishing being overtaken by more targeted and higher value fisheries as populations increase. Large markets can have a disproportionate influence on fishing effort, provided those markets can be connected (often a function of infrastructure as much as physical distance).

Economic conditions: available wealth, as measured through GDP or other metrics, can have a dramatic influence on the simple market values of fisheries. Other metrics, including the distribution of wealth, and social measures such as employment may also be important in understanding value independent of currency and national wealth indicators.

Cultural traditions: alongside current economic drivers, societal traditions can be of considerable importance in driving levels of fishing effort and in creating market demand. Perhaps the most obvious of these is a strong tradition of fishing and of fish consumption. Economic development may increase the availability of other protein sources, and other forms of employment. However, fish consumption may still rise, and with it the values of fish. This is demonstrated by China, where average fish consumption has increased from 4.3 kg per person in 1961 to 31.9 kg in 2009.

Alternative livelihoods: in some places, irrespective of cultural traditions, fishing may be encouraged by a lack of alternative livelihoods, while fishing pressures are likely to be low where manufacturing, agriculture or service sectors are strong, and where the relative profits from fishing are low.

Fisheries management: Fisheries management aims to maximise long-term catch from fisheries. Where effective management is in place, it can lead both to stability, and to increased yields compared to unmanaged and over-fished locations. One common management tool in fisheries management can be closure of some areas to secure breeding populations for a wider area, and it is important in such places for values to be calculated over the entire management area. Similarly, unmanaged areas can produce very high value benefits in the short term prior to fisheries collapse. The lower, but more stable returns from well managed fisheries cannot be directly compared to such benefits.

One key metric for assessing final value then, is the fished biomass (Figure 2), ideally broken down by key target species. This value provides a base metric which underpins many other value metrics which might be measured in terms of hard currency, jobs, or food security. Once fishing pressure is high, the management of fishing effort may determine the longer term value and stability of those values.

Selling fish in India. Photo by Adriaan Backer.

Fish is a common source of protein. Photo by Mark Spalding.

CHAPTER 3: RECOMMENDATIONS FOR MANAGEMENT OF MANGROVES AND FISHERIES

In order to maintain, or indeed to enhance, the value of mangroves for fisheries it is critical that every effort is made to manage them appropriately. The need for active management increases with the number of people living close to the mangroves.

Active management has two broad components: maintaining or restoring the mangroves and managing the fisheries. Critical to the uptake of these activities is the establishment of a desire to instigate such interventions, which may require active engagement in science, outreach and education as well as changes to management regimes.

3.1 Avoiding mangrove loss

Mangrove loss has been driven in large part by conversion to other uses. Perhaps the biggest single driver has been conversion to aquaculture ponds, but large areas have also been converted to agriculture and to more intensive uses such as urban and industrial expansion. In a few places such conversion may bring genuine benefits, but all too often such conversion is justified on incomplete economic arguments and short time horizons. Many aquaculture ventures are only highly profitable for a few years before productivity declines dramatically; meanwhile many aquaculture benefits are typically concentrated in the hands of a small number, while losses may be felt by a much wider community. Many areas of agriculture conversion have been unsuccessful as soils have become saline or acidic. Meanwhile any developments in intertidal areas are an increasingly risky proposition particularly in the face of accelerating sea level rise.

Avoidance of mangrove loss is most effectively achieved through regulation protection and/or the development of strong local or community level ownership.

Some countries have established **blanket protection** at national or regional levels, thus in Tanzania, and Malaysia, mangrove areas are state owned, by law, and there are strict regulations to control or prevent loss. In Australia and Florida, permitting requirements for mangrove loss are often granted only under some provision of "no net loss", requiring that any mangrove loss is compensated by some restoration in other locations.

Protected areas are another widely used tool, and over a quarter of the world's mangroves are located in areas designated for nature conservation. The regulations around protected areas are highly variable, and in some cases active management and harvesting may be permitted, but full-scale clearance would unlikely be permitted in any protected area.

Local or community level ownership has proved a powerful tool for protection in many countries. Such ownership contrasts markedly with both private ownership and full open access. Individual private ownership has often led to damage and loss, while full open access can lead to the "tragedy of the commons" with over-utilisation leading to degradation or loss of the resource. Limited ownership of resources, following Orstrom's model of "common pool resources" (Ostrom 1990) has often promoted wise and sustainable use in communities in communities in the Philippines, for example.

Controlling ex situ threats can be another critical activity, which may require engagement with a much wider group of stakeholders depending on the nature of the threats. Such controls may include inland modifications of dams and irrigation, alteration of coastal development and engineering works, regulation of extractive industry such as oil and gas.

3.2 Restoring mangroves

Mangroves are robust opportunistic species, which means that they can re-colonise or recover in many areas where they have been lost, and will also establish themselves in new areas where soil and hydrological conditions are good. Such recovery can be enhanced with a variety of interventions, but it is also important to note that it is almost always more cost-effective to prevent mangrove loss than to allow loss and to have to invest in rehabilitation or restoration.

Around the world hundreds of thousands of hectares of mangroves have been actively planted in mangrove restoration projects from Bangladesh to Cuba, and from Florida to Australia. Not all restoration projects have been successful, but likewise many areas of mangroves have re-established themselves without active planting or management (Lewis III and Brown 2014).

There is not a large literature on the fisheries production value of restored or recovering mangroves. However it seems likely that fishery benefits do recover following mangrove restoration, although this may take time (Bosire et al. 2008). Younger and less diverse forests will have lower productivity, and the simplistic structure of a young plantation may be less effective in producing fish than a more physically and ecologically diverse mangrove system.

Before any efforts are made towards restoration it is critical to understand both the cause of original loss and the current ownership and regulatory regime. There is simply no point in restoring mangroves if the threat to their existence remains, or if the present owners do not want, or do not stand to gain, from mangrove restoration. Assuming that enabling conditions are good, however, there are some valuable interventions.

Restore hydrological conditions. Widespread mangrove loss has been caused by deliberate or accidental physical disruption to the mangrove sediments – in the case of aquaculture this typically involves the building of dykes and basins, often leaving only narrow areas of intertidal sediments where mangroves can colonise. Restoring a more natural and even surface can be achieved at small-scales by local communities, but can be greatly facilitated by heavy earth-moving machinery, taking down dykes and even creating more natural drainage channels to encourage tidal flows. In many places tidal flows have been interrupted by the building of roads which have then cut off natural water movements. Such flows can often be restored without complete removal of the infrastructure, but with the building of channels or tunnels to restore semi-natural tidal flow regimes.

Restore sediment supply. A loss of the supply of sediments may be an important driver of erosion and mangrove loss in many areas. This can include riverine sediments failing to reach estuarine and deltaic settings as a result of upstream water abstraction and the building of dams as observed in the Indus Delta in Pakistan (Gupta et al. 2012). It can also include the natural movements of sediments along coasts: erosion along muddy coasts in Thailand, China, Java, Suriname and Guiana has been linked to the conversion of wide parts of the mangrove to aquaculture or agriculture. These changes have greatly decreased onshore sediment fluxes across the remaining, narrow mangrove strip and led to net erosion along what had been stable or accreting shores (Winterwerp et al. 2013). Restoring such settings may require highly active interventions, and a number of communities are experimenting with approaches such as the building of semi-permeable barriers to trap sediment, combined with mud nourishment or agitation dredging to enhance sediment in the water column (Winterwerp et al. 2013)

Restore freshwater flows. Many of the most abundant, diverse, and productive mangroves are found in estuarine and deltaic settings where they benefit from more brackish waters and there is evidence that decreases in freshwater inputs into these settings has led to decreased diversity among mangroves and to loss of primary productivity, with a knock-on impact on fisheries.

Allow natural recovery. In many places mangroves will recover naturally simply following the restoration of conditions of hydrology, sediments and/or freshwater inputs. In some places such natural recovery can be helped by the removal of dense ground-cover from salt-tolerant grasses and ferns which otherwise prevent mangrove colonisation. Natural regeneration is a widespread practise in many mangrove "plantations", and in some places this is facilitated where some larger trees have been left un-harvested to provide new propagules.

Full plantation. Where recovery is not occurring, or appears too slow, it can be enhanced through active plantation. If this is attempted it is critical to follow natural requirements of mangroves. Expensive and catastrophic failures in mangrove restoration have taken place because people attempted to plant the wrong species, often in the wrong places. Mangroves are intertidal species which grow best above mid-tide levels. Planting them in deeper water areas may seem an easier proposition, particularly where higher elevations are privately owned, but mangroves cannot grow out of their depth. Likewise the easiest species to plant, such as the large *Rhizophora* propagules, will not always grow on exposed outer margins. Ideally plantations should mimic nature, replicating density, structural complexity, and natural restocking, using multiple species with natural zonation.

3.3 Managing fisheries

Maintaining or restoring mangrove coverage and health may be critical to securing the natural fish production properties of mangroves. However, in many heavily fished locations, fish production is primarily constrained by the impact of fishing itself, with overfishing or destructive fishing practises reducing the productive capacity of the stocks. Few stocks are sufficiently well understood or modelled to be able to know exactly what natural stocks should look like, or to be able to model or predict Maximum Sustainable Yields. Even so, precautionary management can lead to improved yields and increased profits and many of the standard fisheries management methods can be applied in mangroves:

Local resource ownership and use. Strict local ownership, through systems such as Locally Managed Marine Areas (LMMAs) or Territorial Use-Right Fisheries (TURFs) essentially devolve all ownership of natural resources to a community who will greatly benefit from its ongoing sustainable management, and will often actively police this area, preventing use by outsiders.

Gear or harvest regulations. Certain approaches – such as the placing of gillnets across major channels, the use of non-discriminatory gears with excessive bycatch, or the cutting of aerial roots in order to harvest mangrove oysters – are unsustainable in most settings and direct regulation to restrict or ban such practises may be a critical component of any management. Further regulation may restrict the size of traps or mesh-sizes to reduce catch of juveniles, or set size-limits for the harvest of key species, typically also to protect juveniles, but in some cases to maintain a stock of some of the largest, most fecund, adults in a population.

No-take zones. Many small-scale coastal fisheries have been shown to benefit from the complete closure of all fishing activities in certain "no-take" zones. These zones appear to be most effective in areas where fish are closely linked to a fixed substrate. In those areas no-take zones become refuges which export larvae to enhance recruitment in surrounding fished areas, as well as generating some spill over of adult fish.

Access agreements. Restrictions on who can fish can have a similar effect to more formally agreed spatial use agreements. This may be achieved through government level licensing or more local controls, such as the brush park fisheries in Sri Lanka.

Certification. There is a growing demand in certain export markets for a guarantee of sustainability. For example, the prawn fishery in Northern Australia has achieved certification from the Marine Stewardship Council which may be an important driver of high value sales. This requires that fisheries demonstrate that their fish stocks are sustainable, their environmental impact is minimised and that management measure are effective (Marine Stewardship Council 2013). Similarly, standards for sustainable aquaculture like the Aquaculture Stewardship Council exclude development of aquaculture in mangrove areas and demands rehabilitation of degraded mangroves.

3.4 Communication and engagement

Both mangroves themselves and mangrove-associated fisheries are highly amenable to management interventions which can generate considerable social and economic benefits. For such management to be undertaken there needs to be a clear understanding and ideally an accurate quantification of these benefits. Such values must also be communicated to a broad audience. And for any management to be implemented a viable enabling environment must be present in terms of policy and legal frameworks.

Quantifying values. Some of the most effective changes in management can be driven by a real understanding of underlying values, ideally with models of sufficient capacity to enable scenario-building. Such quantification needs to be site specific and more reliable than simplistic extrapolation from studies conducted in other places, or generic statements of global value based on averaged studies. It needs to report in relevant numbers for managers, which may be fishable biomass, jobs, food security, or direct economic values.

As with other fisheries, reliable models will be valuable not only for making a case for mangrove-associated fisheries management, but in driving the ongoing management of the fishery through time as conditions and stocks fluctuate.

Communicating value. The value of mangrove-associated fisheries, and of mangroves to offshore fisheries, is often underestimated or overlooked, in some cases even by the fishers themselves. In order to drive a change in the way mangroves are managed it may be necessary to challenge such views, reaching out to multiple sectors from coastal populations to consumers of mangrove produce to coastal developers and senior policy-makers, including economists. Such values need to be communicated simply in relevant metrics. Ideally they should be placed alongside alternatives, with trade-off analyses enabling all sectors to understand all relevant costs and benefits.

One key additional component in understanding mangrove value is to consider fisheries values alongside other benefits. Mangroves provide a whole bundle of ecosystem services of which fisheries may only be a small fraction. This may be in stark contrast to alternative uses such as aquaculture or built sea defences. Aquaculture may, in some places, or in the short term, generate higher economic returns, but will not provide coastal defence, carbon storage or water purification. Sea walls may provide defence against storms with a smaller spatial footprint, but replacing mangroves with sea walls leads to loss of associated fisheries enhancement, timber provision and other benefits.

Creating an enabling environment. Even when there is understanding of the value of mangroves, and a willingness to make management changes there may be a need for reform of legal, policy and tenure frameworks. Key among these may be reform of subsidies that encourage mangrove conversion to aquaculture or coastal agriculture.

The treatment of mangroves as "common goods" can drives over-harvest and loss, but fully private ownership may also encourage conversion to the detriment of the wider community. Building a more robust tenure system can go a long way towards ensuring continued or enhanced productivity.

Another key feature of mangroves is their ability to provide key goods and services over indefinite timescales. Financial and development planning needs to avoid the trap of focussing on narrow timescales, such as electoral cycles, when considering the value of mangroves, but to build in the ongoing provision of benefits in perpetuity as a highly valuable feature of these ecosystems.

Coastal Fishery in Java, Indonesia. Photo by Alexander van Oudenhoven

CHAPTER 4: CONCLUSIONS

Mangroves enhance fish production via two key mechanisms – the provision of food and of shelter. High levels of primary productivity within the mangrove forest provide the basis of food chains that enhance the growth of many fishery species. At the same time, the three dimensional structure provided both by the complex of channels and pools, and by the complexity of roots and branches, gives shelter from predation and beneficial physical conditions such as shading and reduction of water flows. Some commercially important species of crabs and some finfish live year-round in mangroves, but for many other species, including many finfish and prawns, mangroves are of particular importance as a nursery habitat.

The science underpinning our understanding of the role of mangroves is rapidly growing, and there is an increasingly strong body of evidence supporting their effects in enhancing coastal and cross-shelf fisheries. This includes correlations between catches of fish and mangrove area (e.g. Paw and Chua 1991, Aburto-Oropeza et al. 2008), higher abundances of fish (particularly juveniles) in mangroves than in other habitats (e.g. Laegdsgaard and Johnson 2001, Nagelkerken et al. 2001) and stable isotope studies showing that fish move from mangroves to coral reefs and other habitats as they grow (e.g. McMahon et al. 2011, Kimirei et al. 2013).

A number of authors have sought to summarise mangrove-associated fishery values (Table 1) with estimates suggesting mean values often in excess of US$1000 per hectare per year, but with very broad ranges and median values typically in the order of $10s to $100s of dollars. Our own extensive review suggested a global median value of US $77/ha/yr for fish, and US $213/ha/yr for mixed species fisheries. However, understanding the enormous *variation* in value, illustrated in the tables through this report, is far more important than establishing ever more accurate global totals or average numbers. Values, which can be stated in simple catch statistics, in monetary terms or other metrics, are site specific and it is at these sites or places that management decisions, conservation actions and fishing activities take place. In order to be able to make decisions we need to know or predict actual or potential value in these precise locations. In turn this requires an understanding on what external factors may drive value.

Ideally, a detailed numerical model of mangrove-associated fisheries should be built up from field and experimental data, which could then form a basis for predicting value in other locations, and for modelling potential values in future planning. As part of the current work we began a review of over 1500 papers on mangrove-associated fisheries. Despite this impressive base, we did not find the data that would enable us to determine how these drivers interact to produce the range of observed values. The complexity of the different fishery types, scales, and fishing methods, coupled with the range of different study methods and reporting units, meant that we were unable to develop a model linking the drivers to the observed catches. This represents a data gap in the current literature. Such a gap could be addressed by further studies, particularly if they report their findings using standardised measures of fishing effort and catch. Such measures are available in the literature (e.g. Salthaug and Godø 2001, Maunder and Punt 2004), but they mostly compare different fishing vessel sizes so would not cover the varied techniques used in small-scale mangrove-associated fisheries.

The review work has helped to inform a detailed understanding of many of the fisheries and a generalised understanding of the processes which drive value, and from this work we have developed a simple conceptual model of the key drivers of fisheries value, including the biophysical factors that determine how many fish a mangrove produces, and the socio economic factors that determine how many of these fish are caught by humans, and what they are worth in economic terms, as a food supply or through the livelihoods that they support. From these we can predict where mangroves are likely to be particularly valuable to fisheries:

Mangrove dependent fishers in Latin America. Photo by Wetlands International.

- Fish productivity from mangroves will be highest where mangrove productivity is high, where there is high freshwater input from rivers and rainfall and where mangroves are in good condition.
- Fish productivity will increase with an increase in total area of mangroves, but notably also with the length of mangrove margin since generally it is the fringes of mangroves where fish populations are enhanced. This will also be influenced by geomorphology, with the network of channels, pools and lagoons all contributing to the margin length.
- Moreover, mangroves with greater structural complexity will enhance fisheries to a greater extent. The structure of roots varies between different mangrove tree groups, and is important for shelter that the roots provide to juvenile fish and prawns, and attachment points for bivalves.
- Fish catch will be highest close to areas of high human population density that provide the fishers and the markets for the catch. Of course some of these mangroves close to populations are also likely to be under greater threat than those in more sparsely populated areas – they may be degraded, the waters may be polluted, or they may be over-fished and hence less productive. Where such mangroves are secured through management regimes, and where their fisheries are well managed they are likely to give greatest value. Conversely, conservation and restoration efforts in these areas close to human populations will likely give the greatest return on investment.

APPENDIX 1: FISHERY CASE STUDIES

These case studies give representative examples to support the discussion of mangrove fishery types in section 2. They also provide insights into the range of fisheries management alternatives currently in practice and their perceived efficacy. Numbers used in discussion of catches come from the FAO via the *FishstatJ* software package (FAO 2011), unless other sources are cited.

Inshore mixed species fisheries

Case study: Brush park fisheries

Description: Brush parks are clusters of twigs and branches stuck into the muddy bottom of shallow lagoons. They are built and left in place for a period of a week to a month or more, after which the fish are harvested by surrounding the brush park with a net and removing the branches. These twigs and branches often come from mangroves, and the lagoons where the fisheries operate are often fringed by mangroves. Many of the species caught are therefore also likely to be linked to mangroves, and it seems likely that the structure of submerged branches mimics mangrove habitats. They are found in West Africa, Madagascar and Asia, including Bangladesh, China, India, Sri Lanka and Cambodia (Welcomme 2002). The technique has also been introduced to some lagoons in Mexico (Baluyut 1989).

This case study focusses on the brush park fishery in the Negombo lagoon on the west coast of Sri Lanka. The data comes from two papers, one by Costa and Wijeyaratne (1994) and the other by Amarasinghe et al. (2002).

Site: The Negombo lagoon is a shallow lagoon with a water surface area of 3502 ha. Around the edge of the lagoon are roughly 350 ha of mangroves, the branches of which are used in brush park construction. The lagoon has a large brush park fishery, with 2-3000 brush parks accounting for just over a third of the total fish catch in the lagoon.

Brush park construction: Most brush parks are 6-12 m in diameter, and use 300-600 branches inserted into the bottom vertically or at a slight angle. Brush parks are constructed in areas of the lagoon with a muddy bottom and moderate water currents. Most brush parks are left for 2-3 weeks before harvesting, which is a trade-off between total catch and waiting time. Amarasinghe et al. (2002) found that yield of finfish and catch value rise at a decreasing rate until plateauing after around 40 days, but the need for immediate income means that they are rarely left this long. Yield of crustaceans appears to rise steadily even up to 60 days, but they are a small part of the total catch. The brush park is harvested by surrounding it with a net, removing the branches and using a scoop net to capture the trapped fish. After harvesting the brush park is reconstructed using the same twigs. The branches are generally replaced annually.

Catch statistics: In the 1998-99 fishing season, the total catch was 12.46 t ha^{-1} brush park yr^{-1}. 84% of this yield was finfish, with the rest made up by crustaceans. The fish species caught vary with season and location in the estuary, with the green chromide chichlid *Etroplus suratensis* often making up the majority of the catch. Other main food fish included seabream (Sparidae), eel catfish (Plotosidae), gobies (Gobiidae), silver-biddy (Gerreidae), barramundi *Lates calcarifer*, mullet (Mugilidae) and rabbitfish (Siganidae). Grouper (Serranidae) species are sold live for aquaculture and rarer chichlids are caught in small numbers and sold live for the aquarium trade. Crustaceans include mud crab *Scylla serrata*, and sub-adults of a number of species of penaeid prawns. Mean catch value was 228 Sri Lanka Rupees, equivalent to US $2.9, per brush park harvested. This gives an annual income of around US $35 per brush park, assuming each park is harvested 12 times annually, which equates to a total value of US $75,000 – $105,000 annually for the lagoon as a whole.

Sustainability: Like most fishing methods, brush parks have the potential to over-exploit fish populations. This did not appear to be a problem in the Negombo lagoon at the time of the studies used as sources for this case study. Although the brush park fishery is not managed through any legal framework, access to the fishery is limited by social factors. The total number of brush parks in the lagoon is limited by the availability of space in the most profitable areas, determined both by fish abundance and by suitable depth and bottom composition. Brush parks in these areas are generally controlled by a single village. These "owners" are territorial towards outsiders trying to construct brush parks in their area, through direct aggression or the destruction of their brush park. Fishing rights to particular areas are passed down in families. This limited access helps to prevent overfishing. In other parts of the world, brush parks may be used as a form of aquaculture to enhance fish populations. In Benin, for example, large, permanent brush parks are used to provide a breeding habitat for fish. Smaller brush parks around the large central one are then used to catch fish emigrating from the central park. This system enhances fish populations, making it inherently sustainable (Welcomme 2002).

Brush parks also have an environmental impact on mangroves and other forests through the wood that is cut and used in their construction. In the Negombo lagoon, this had led to the development of mangrove cultivation, where mangroves are grown for construction of brush parks and for poles for terrestrial building. This relieves pressure on the natural mangrove forests, also helping to protect the fish stocks that depend on them.

Inshore crustacean fisheries

Case study: Scylla serrata (mud crab) fishery

Description: The mud crab *Scylla serrata* (called the Indo-Pacific swamp crab by the FAO) is amongst the most important commercial crab species in the world. It is found in estuarine habitats, particularly mangroves, throughout the Indo-Pacific, occurring from the east coast of Africa through to Polynesia in the Pacific, south as far as New Zealand and north to Okinawa, Japan. It has also been introduced to Hawaii and to the Gulf of Mexico. It is a large crab, reaching up to 3 kg in weight, with flattened back legs for swimming and strong, heavy pincers, which it uses to feed on molluscs, other crabs and occasionally fish.

Catch statistics: In 2010, the global reported catch was 37,000 tonnes (FAO 2011, Grubert et al. 2012), although this is likely to include other species from the genus *Scylla* which are misidentified. 30,000 tonnes of this came from Indonesia, with the Philippines, Thailand and Australia accounting for the majority of the rest. Many countries within the mud crab's range do not report catches of mud crab to the FAO, and these figures also do not account for the unreported catch in subsistence and recreational fisheries. The total global catch is therefore likely to be much higher than the FAO figures suggest. Mud crabs are highly prized for their sweet tasting flesh and can command high prices with websites in Australia selling them for US $35/kg as of January 2014.

Catching methods: Mud crabs are often caught using pot traps set in mangrove channels or just offshore. Hand collecting and use of a wire loop to hook crabs out of their burrows is also common, particularly in developing countries.

Sustainability: In many countries, mud crab fisheries are unregulated, particularly where fishing is primarily artisanal. Mud crabs produce large numbers of offspring which have high dispersal ability as pelagic plankton, meaning that they are able to withstand moderate fishing pressure. Nonetheless, catches and average sizes are decreasing in parts of the mud crab's range, indicating overfishing (e.g. Ewel 2008, Kosuge 2001). In countries where mud crab fisheries are regulated, minimum size limits appear to be very effective at maintaining stocks. Some areas also ban taking of female crabs, which have higher natural mortality due to their migration to and from deep water to spawn.

Case study: Ucides cordatus (mangrove crab) fishery

Description: *Ucides cordatus* is known as the mangrove crab (although that name can also be applied to numerous other species), or by its Portuguese translation "caranguejo-uçá". It is found on the tropical Atlantic coast of the Americas, from the south of Brazil through the Caribbean and the Gulf of Mexico to Florida in the north. It is a semi-terrestrial species, sheltering in burrows at high tide and emerging to feed when the tide recedes. It is almost invariably associated with mangroves and plays an important ecological role by recycling large amounts of mangrove leaf litter on which it feeds. It has a tall, egg shaped carapace and reaches a maximum size of around 280 g (Ivo et al. 1999). Females are smaller than males, which makes them less commercially valuable.

Catch statistics: The FAO does not record catches of this species, so there is little data on the total catch. However, catch data does exist in the scientific literature for a number of individual estuaries. In the state of Piauí, average annual production from 1994-1999 was 1,093 tonnes, with the majority of this coming from the Parnaíba River delta. North-east Brazil as a whole produced 7,452 tonnes per year over the same period (Ivo et al. 1999). In the Caeté Estuary in Pará, Diele et al. (2005) report average annual catches of 1200 tonnes between 1997-2003, equivalent to a productivity of 85 kg ha^{-1}. Extrapolating this figure to the whole of Pará and the neighbouring state of Maranhão, they estimate a potential catch of 76,000 tonnes per year assuming that 60% of mangrove stands are accessible to fishers. Thus it is clear that the species is of significant importance to fisheries throughout the region.

Catching methods: Catching methods are often highly specialised. They can be divided into two broad classes: hand collecting and traps. Hand collecting methods include "tapamento" and "braceamento". The "tapamento" technique involves a complex set of actions, including widening the opening of the burrow, then blocking it off with a ball of mud and tree-roots inserted into the widened opening (Nascimento et al. 2012). This apparently causes the crab to become disorientated, making it easy to capture when the stopper is removed from the burrow (Nordi et al. 2009). Collectors leave stoppers in the burrows for a period of time, following a circular route so that they can return to stopped-up burrows to capture the crabs. "Braceamento" is a simpler technique, in which the crab collector inserts their arm into the burrow of the crab and catches the crab by its shell. "Braceamento" is more productive, as crab collectors do not have to follow a pre-defined route or visit burrows more than once. However, "tapamento" is more selective, and crabs captured using this technique were 12% larger on average in a study in Paraíba, Brazil (Nordi et al. 2009).

Two types of traps area commonly used. A "redinha" is a snare made from a shredded polypropylene bag. They are placed over the entrance to crab burrows and secured in place with stakes cut from mangrove prop roots (Nascimento et al. 2012). When crabs attempt to emerge from their burrows, they become entangled in the snare and are caught. This technique is illegal in Brazil, due to its lack of selectivity and the damage that root-cutting causes to the mangrove. However, a study in Rio Grande do Norte found that 74% of collectors were using this technique, although all reported that they captured crabs manually (Capistrano and Lopes 2012). The second trap type is called a "forjo" and involves an oil can or plastic bottle with a door. The door is sprung using rubber from a bicycle inner tube, and is triggered by a system of levers when a crab touches the bait inside the trap.

Sustainability: In Brazil, mangrove crab fisheries are regulated to some extent, including a closed season during the crabs' mating period when the crabs leave their burrows and are easily caught, and a ban on certain capture methods. However, as discussed above, enforcement of these regulations is often lacking. Like mud crabs, mangrove crabs have high fecundity and are relatively resistant to overfishing. Market forces also regulate harvesting, with strong demand for large crabs meaning that females and immature males have little commercial value and are rarely harvested (Diele et al. 2005). However, pressure on populations has increased recently due to an influx of migrants into coastal areas coupled with high unemployment. Crab fishing is open access and has low entry costs, making it an attractive option for people who are unable to find other work. Use of non-selective trap-based methods has also increased, possibly because these techniques provide more success to inexperience collectors. As a result, signs of overfishing are appearing in some areas, including diminishing catches and reduced average size of crabs (Nordi et al. 2009, Capistrano and Lopes 2012).

Case study: Inshore prawn fisheries for aquaculture

Prawns are an extremely popular food globally and form the basis of a high-value fishery. Some of the highest values species, mostly in the family *Penaeidae*, appear to have a strong degree of dependence on mangroves as nursery grounds. The adults migrate offshore after several months in the mangroves, where they are targeted by a large offshore prawn fishery (see the following section on mangrove offshore fisheries). The juveniles within the mangroves also support local fisheries for larvae, which are sold on to aquaculture facilities.

Description: For many of the most important commercial prawn species, aquaculture production dwarfs production from wild-capture fisheries. For example, aquaculture production of the giant tiger prawn *Penaeus monodon* was 3.5 million tonnes in 2011, compared to just 222,000 tonnes from fisheries. Similarly, aquaculture production of the giant river prawn *Macrobrachium rosenbergii* was 1.1 million tonnes whilst only 11,000 tonnes were caught in the wild. Aquaculture ponds are stocked with post-larvae, the stage in prawn development following metamorphosis from a nauplius to a miniature version of the adult. Although hatcheries are increasingly being used to supply juveniles, in many parts of the world prawn aquaculture is still heavily dependent on wild-caught post-larvae. Wild post-larvae are considered to be of better quality and have higher survival than hatchery-produced post-larvae. Both freshwater and marine prawn species use mangroves as nursery grounds, so fisheries for prawn larvae tend to be undertaken within the mangroves themselves.

Catch statistics: Prawn post-larva fisheries are often small-scale, carried out by the poorest members of society. As such, they tend to go unreported and do not appear in FAO data. Bangladesh does not report any wild prawn capture, despite producing around 300,000 tonnes of *M. rosenbergii* and 390,000 tonnes of *P. monodon* in 2011. However, Nuruzzaman (2002) estimates that 1.5-2 billion prawn post-larvae are collected from the wild each year in Bangladesh, with a value of around US $30 million. Aquaculture in Bangladesh in 2002 when this estimate was made produced just over 1% of the total global production in 2011, implying that current global prawn larva catch could be 100 times this estimate, although this will be partially offset by improvements in efficiency and greater use of hatchery-produced post-larvae.

Harvesting methods: Fisheries for prawn post-larvae are often carried out on small scales by the poorest members of society, who have no income from other sources. Methods used tend to reflect this. In Bangladesh, two main methods are used to fish for post-larvae of *M. rosenbergii* (Ahmed and Troell 2010). Pull nets are nets mounted on frames 2-2.5m wide, which are dragged behind the fisher at the surface as they wade against the current in shallow water. Set bag nets (see "Stow nets" in table 1) are fixed in position at the surface in areas with deeper water and strong currents. They are larger than pull nets, up to 5 m wide, and catch prawn post-larvae as they are swept into them by the current. In other regions, seine nets may also be used in shallow areas such as mangrove channels. All nets used must have a fine mesh, as prawn post-larvae are small.

In regions where aquaculture is less intensive, prawn post-larvae may be collected through the tidal inflow of water into ponds. This system is used in the Mekong delta in Vietnam, where ponds are built within a network of tidal channels in former mangrove. Sluice gates connecting the pond to the channel are opened to allow water and the prawn post-larvae in it to enter the pond. The pond is then closed for a period of time to allow growth of the prawns, then harvested by draining the water back into the channel through a net.

Sustainability: Studies in various regions, including Bangladesh and Vietnam, report declining catches of prawn post-larvae. The huge numbers of post-larvae being caught in Bangladesh suggest that overfishing might be one of the causes for this decline, coupled with wild-capture and broodstock fisheries for adults. Destruction of mangrove nursery grounds is also a factor, and this is likely to be particularly important in the Mekong delta where brackish water aquaculture increased by almost 400% between 1985 and 1994 (Johnston et al. 2000). This is a sustainability issue for pond aquaculture in general, rather than the prawn larvae fishery alone.

Beyond the potential for overfishing, the biggest sustainability issue with prawn larvae fisheries is the high bycatch. This is the result of the fine-mesh nets used, which catch everything that enters them, along with the comparative rarity of the target prawn larvae compared to other more common fish and crustacean species. In both pull nets and set bag nets in Bangladesh, over 90% of the catch was non-target species (Ahmed and Troell 2010), while in the Indian Sundabans prawn larvae make up only 0.25% of the catch (Sarkar and Bhattacharya 2003). Pull net catches are sorted on the bank, so bycatch is unlikely to survive. In set bag net fisheries the catch is sorted in a boat, so some of the bycatch may be released alive, but mortality will still be high for animals such as sea turtles, which drown in the net, or for fish that require forward movement through the water for respiration.

Concerns about overharvesting and bycatch have led to attempts by governments to regulate prawn larvae fisheries, but these regulations are frequently not enforced. In Bangladesh, fishing for prawn larvae was banned in September 2000, but this ban has had little effect due to a lack of motivation and resources for enforcement, as well as a lack of alternative livelihoods for those involved in prawn larvae fishing (Ahmed and Troell 2010). Similar situations exist in India and other countries where prawn larvae are harvested to supply the aquaculture industry.

Inshore bivalve fisheries

Case study: Mangrove oysters

Description: Oysters are bivalve molluscs in the family Ostreidae. They have irregular, ridged shells, which mould themselves to the shape of the substrate on which the oyster grows. Many oyster species can live on mangrove roots and a few are mangrove specialists. Inside the shell, the oyster has a fleshy body. The amount of meat varies significantly with the spawning cycle, with shells being fullest immediately before the oysters spawn. In many countries they are considered a delicacy eaten raw, but they are also often cooked and may be dried or salted as a preservation method. In the Atlantic, the main species are *Crassostrea rhizophorae* from the Americas, *Crassostrea tulipa* from West Africa (Vakily et al. 2012) and *Crassostrea gasar*, found on both sides of the Atlantic (Lapègue et al. 2002). In the Indo-Pacific these are replaced primarily by species of the genus *Saccostrea*, including *Saccostrea cucullata* (Jana et al. 2013), and *Saccostrea echinata*. All species use mangroves as a solid substrate to grow on in an otherwise muddy environment. Like most bivalves, oysters feed by filtering algae from the surrounding water.

Catch statistics: The wide diversity of species and the challenges in identifying oysters to species level makes it difficult to estimate the global catch of mangrove oysters. Some Caribbean countries report catches of mangrove cupped oyster (probably *Crassostrea rhizophorae*) to the FAO.

Catches have declined in recent years, but peaked at 4705 tonnes in Venezuela in 1990 and 2316 tonnes in 1989 in Cuba. Other countries with significant mangrove areas are likely to have similar harvests, although in many areas stocks and harvests have declined due to overharvesting (e.g. Appeldoorn 1997, Mendonca and Machado 2010).

Harvesting methods: Mangrove oysters are collected by hand at low tide, either on foot or from a small boat. They may be cut from the mangrove roots with a small knife, or the whole root may be cut and the oysters removed later. In many areas, oysters are cultured on artificial 'mangroves', made by suspending tree branches in the water from a man-made pier or jetty. These can be placed below the low-tide mark, which enables the oysters to feed continuously giving faster growth rates.

Sustainability: Like crabs, oysters have high fecundity. In addition, they are fast growing, attaining harvesting size at 4-5 months and can spawn as little as three months after settling (Mackenzie 2005). Mangrove oysters are also less vulnerable to over-harvesting than reef-forming oyster species, as the mangrove trees provide the hard substrate they require to settle on, as opposed to relying on their own shells as a substrate for recruitment. Their reliance on mangroves for substrate, however, makes them very sensitive to clearance of mangrove forests. Fishing techniques that involve removing sections of mangrove root along with the attached oysters, rather than removing the oysters from the root can contribute to mangrove loss.

Most of the fisheries that have been studied have some level of management, including minimum sizes and closed seasons. However, these are often weakly enforced. In particular, the minimum size limit may be circumvented by selling shucked oysters without their shells (Mendonca and Machado 2010). Oyster recruitment varies naturally, which can lead to overharvesting in years when recruitment is low but fishing effort remains high from previous years. Like crab fisheries, mangrove oyster collecting also has a low barrier to entry, meaning that socio-political conditions can lead to an increase in the numbers of oyster collectors. These factors have led to declines in oyster stocks in some fisheries, but the oysters' fecundity means that stocks can recover rapidly if fishing pressure is reduced. Stocks can also be enhanced by culturing, which ranges from simply placing mangrove branches in the water to collecting spat on specifically designed collectors and transplanting these onto growing surfaces (e.g. Buitrago and Alvarado 2005).

Case study: Mangrove cockles

Description: Mangrove cockles are bivalves in the genus *Anadara*. They are in the ark shell family Arcidae, but bear a strong resemblance to the true cockles (Cardiidae) with radial ridges on the shell extending from the hinge. Not all *Anadara* species are mangrove dependent. This case study will focus on the small-scale commercial fisheries on the Pacific coast of Mexico and Central and South America.

Catch statistics: Mexico, Costa Rica and Ecuador all report catches of mangrove cockles to the FAO, and harvested 654, 45 and 599 tonnes respectively in 2011. Other countries in the region do not report catches to the FAO, but probably take similar catches. Columbia in particular has large sections of mangrove coastline and in a 2001 study had similar estimated numbers of cockle collectors to Ecuador (Mackenzie 2001). The blood cockle (*Anadara granosa*) is found throughout the Indo-Pacific from Africa to Polynesia (FAO 2014), and is harvested in large quantities, with Indonesia alone producing 39,000 tonnes in 2011. This species is, however, less mangrove dependent, therefore not all of this catch can be attributed to mangrove areas.

Harvesting method: Mangrove cockles are harvested by hand, by probing in the mud for cockles buried beneath the surface. In some locations, fishers also dive for cockles growing in the bed of rivers. Different species are found at different depths, with *Anadara grandis* often found protruding slightly above the surface, *A. tuberculosa* at wrist depth and *A. similis* requiring inserting the arm into the mud up to the elbow. Harvesting conditions are harsh, with deep mud and potential for injury from sharp mangrove roots, shells and fish species with sharp spines. Many collectors therefore wear gloves or fabric tubes on each finger to protect their hands. Cockle collecting communities are generally amongst the poorest in their countries, and cockle collecting generally includes a subsistence element, with collectors keeping some of the catch to feed their own families. The rest is sold to provide a small income. In small villages this may be directly to consumers at stalls by the roadside, whilst in larger settlements it tends to be to dealers, who then sell them on to restaurants.

Sustainability: As with oysters and mangrove crabs, harvesting pressure on mangrove cockles is heavy due to the low barrier to entry and the lack of alternative livelihoods and food sources for many cockle collectors. Most countries have minimum size limits for cockle collecting, but enforcement is variable. Catches and average sizes have fallen in Ecuador (Beitl 2011) and one species is listed as vulnerable in Colombia (Lucero et al. 2012). In 2000, local collector associations in two regions of Ecuador were given the right to manage their own fisheries. The managed areas, known as *custodias*, have greater catch per unit effort and larger average cockle sizes thanks to the strict management, but are controversial due to the exclusion of non-members from the managed areas. In general, whilst cockle populations are vulnerable to depletion by overharvesting, they are safeguarded by cockles living in impenetrable mangrove stands which can replenish the population of the surrounding areas. A more serious threat is the loss of mangrove area through conversion to shrimp farming, which accelerated rapidly in the region in the 1980s and 1990s.

Offshore fisheries

Case study: Fisheries for adult prawns

Description Of all the offshore fisheries that have been linked to mangroves, the fishery for prawns is the one with the most robust evidence. Numerous studies exist showing positive correlations between mangrove area and catch of various prawn species (Manson et al. 2005). Juvenile prawns of many commercially important species are widespread in mangroves (Rönnbäck et al. 1999, Vance et al. 2002), and at least some of these juveniles are much less common in other estuarine habitats (Robertson and Duke 1987, Chong et al. 1990). Commercially important species for which mangroves appear to be particularly crucial as nursery habitats include the banana prawn, *Penaeus meguiensis*, the Indian white prawn, *Fenneropenaeus indicus*, and the greasyback shrimp, *Metapenaeus ensis*, as well as freshwater river prawns in the genus *Macrobrachium,* which migrate to brackish water to spawn. Some of the prawn fishery catch will be consumed domestically, but much will also be exported along with prawns produced by aquaculture. The top importers of penaeid prawns are European countries, importing over 300,000 tonnes between them in 2009. In some countries, egg bearing females are separated from the rest of the catch as broodstock, which are used to supply larvae to hatcheries. They are usually caught in prawn trawls, but are kept alive due to their high value for producing juveniles, which may range to hundreds or even thousands of dollars per egg-bearing female (Rönnbäck et al. 2003).

Catch statistics: Prawn fisheries are better reported and monitored than many smaller scale mangrove-associated fisheries. 11 species found in mangrove regions had catches of over 10,000 tonnes in 2011, and five had catches over 100,000 tonnes. These species were: Southern rough shrimp *Trachypenaeus curvirostris* (293,000 tonnes), giant tiger prawn *Penaeus monodon* (222,000 tonnes), oriental river prawn *Macrobrachium nipponense* (138,000 tonnes), fleshy prawn *Fenneropenaeus chinensis* (126,000 tonnes) and banana prawn *F. merguiensis* (102,000 tonnes). A number of other species are also important but less well recorded, due to the level of monitoring in the countries in which they are caught. The total global catch of mangrove-related prawns is thus likely to be somewhere over 1 million tonnes, and is highly valuable; the prawn fishery in Bintuni Bay, Indonesia is worth over US $6 million annually (Ruitenbeek 1994).

Catches of egg-bearing females for hatcheries largely go unreported. However, one study in Andhra Pradesh on the east coast of India found that an average hatchery used around 900 egg-bearing females annually, and produced around 60 million larvae, each individual thus producing around 70,000 larvae (Rönnbäck et al. 2003). Mortality is significant at all stages of the process, with up to 10% of females failing to spawn in hatchery conditions, 10-25% off eggs failing to hatch and 50-70% of the hatched nauplii not surviving to become post-larvae. However, mortality in the wild is likely to be equally high due to predation. Extrapolating from these figures, it might require 20 million female spawners to supply the entire global aquaculture industry. Assuming a weight of 100g per individual, this would be a catch of around 2000 tonnes. This is a very small part of the 972,000 tonnes of mangrove-related prawns harvested in 2011 and in reality many shrimp farms use wild-caught post-larvae rather than those from hatcheries. Thus whilst the fishery for prawn broodstock is locally important, especially because of their high value, it is small in comparison to wild-capture prawn fisheries.

Catching method: Commercial fisheries for adult penaeid prawns primarily use various forms of trawling. Most penaeid prawn species live on or close to the bottom, so trawling is the only feasible method to catch them. Common trawling methods include otter trawling, where large rectangular boards are used to open the net, and beam trawling in which the net is held open by a rigid beam. Large, powerful boats may drag three or four nets simultaneously, enabling them to cover a strip of the sea bed 50 m wide or more in a single pass. Fisheries for *Macrobrachium* river prawns are generally smaller in scale as they are based in rivers and estuaries, and tend to use a mix of traps and seine nets.

Sustainability: Environmental concerns associated with prawn trawling include high levels of bycatch, damage to sensitive communities on the sea bed and overfishing of the prawns themselves. Bycatch is a particular problem, with 62% of the total catch being discarded, and prawn trawl fisheries accounting for 27% of the total discards across all capture fisheries (Kelleher 2005). This is the result of the small mesh sizes required to retain prawns, as well as the relatively low biomass of prawns compared to other species on prawn fishing grounds. Fishing grounds are also often long distances from markets where bycatch could be sold, meaning that much of it is discarded.

The extent to which these negative impacts affect a given fishery depends on the management of the fishery. Due to its commercial scale, prawn fishing often has greater levels of regulation than small scale fisheries. However, the extent to which these regulations are enforced varies widely from country to country. In Australia, the northern prawn fishery targets a range of penaeid prawn species and is tightly managed. The management includes a licensing system, and uses catches as a way of monitoring prawn stocks. If catches fall below a set threshold, that area of the fishery is closed for a period of time or even the rest of the season. There are also laws on bycatch; all nets have to be fitted with a turtle excluder device and any interaction with turtles, sea snakes, sea horses and certain species of shark and ray have to be reported. As a result of these measures the fishery is certified sustainable by the Marine Stewardship Council. By contrast, in Bangladesh, turtle excluder devices were made a legal requirement but this requirement was removed following a high court injunction after trawler owners complained that it would prevent larger commercially valuable fish being caught. Bycatch in this fishery is over 80% of the total, and catches of the target prawn species are also declining indicating overfishing (Rahman 2001).

Recreational fisheries

Case study: Catch and release bonefish in the Bahamas

Description: Bonefish are wary and powerful fish, a combination that makes them challenging and hence appealing to catch for sport. Bonefish are often found close to mangroves and enter them at high tide to feed. The fishery is generally undertaken in the "flats", shallow calm areas, generally just offshore from mangroves This provides a beautiful setting which increases the appeal of bonefishing as a recreation activity. Tourists are the main participants in the catch-and-release bonefish industry in the Bahamas.

Catch statistics: As this is a catch-and-release fishery, it is difficult to report catch numbers, but the importance of bonefishing to tourism can be quantified. Of the 1.5 million tourists who visited in 2004, 0.3% of them primarily visited to undertake bonefishing or fly-fishing (Danylchuk et al. 2007a). Bonefishing contributed US $141 million to the Bahamas in 2008 (Fedler 2010), with some villages almost entirely dependent on this recreational fishing industry (Danylchuk et al. 2007a).

Catch method: Fish are caught from small boats using light fly-fishing and hook and line gears.

Sustainability: As a catch-and-release fishery, bonefish fishing should be sustainable. Catch-and-release can, however, have impacts. Bonefish which are poorly handled following being caught can suffer a high (17%) mortality rate from predation within one hour of release (Danylchuk et al. 2007b). Training in handling and releasing of fish can therefore ensure this fishery remains sustainable in the face of high fishing pressure.

Case study: Barramundi Lates calcarifer recreational fishery in Australia

Description: Barramundi are large, predatory fish found in the sea perch family (Centropomidae). They are found throughout the Indo-West Pacific. They are prized for their fighting ability when hooked, and for the eating quality of their flesh – unlike the Caribbean bonefish fishery, barramundi are often kept for eating, subject to the size and bag limits described below. Barramundi are generally catadromous, meaning they spend much of their lifecycle in fresh water but move to estuaries to breed. Juveniles remain in estuarine habitats, especially mangroves, for 6-9 months before migrating upstream to fresh water. Some may also remain in coastal habitats for life if access to rivers is limited.

Catch statistics: Landings by recreational fishing are usually dwarfed by commercial landings. In Australia in 2010, the commercial catch of barramundi *Lates calcarifer* was 1676 tonnes, whilst the catch in recreational fisheries was 303 tonnes. However, as with the Caribbean bonefish fishery, the scale of the catch does not reflect its value. The Queensland recreational barramundi fishery alone is estimated to be worth AU $8-15 million (US $7.5-14 million) each year.

Catch method: Barramundi are commonly caught by lure fishing, moving a metal or plastic lure through the water to imitate a small prey fish. They are also caught by fly fishing or using natural baits.

Sustainability: In Western Australia the bag limit for barramundi is two per day, and there is also a possession limit meaning that no individual can have more than two barramundi in their possession at any moment in time. There is also a minimum size limit of 55 cm and a maximum size limit of 80 cm (Department of Fisheries Western Australia 2014). Fish outside these limits must be returned to the water. This means that juvenile fish are given a chance to breed, and the largest fish with the highest reproductive output are not removed from the population. Other Australian states have similar regulations. Like other recreational fishery target species, barramundi are large, top-level predators and are longer lived and slower to reproduce than species lower in the food chain, making them vulnerable to overexploitation. In Australia, populations are monitored and bag limits are enforced. However, as recreational fishing becomes more popular as a tourist activity in countries with less strict regulations, it could contribute to the threat to this and other similar species.

Fish in Rhizophora roots. Photo by Mark Spalding.

TABLE 1: FISHING GEAR COMMONLY USED IN MANGROVE HABITATS

Category	Description				
Gear type	Description	Scale of fishery	Target species groups	Location	Sustainability
Seine nets	Seine nets are simple nets that hang vertically in the water column, suspended using floats at the top and weights at the base, forming a barrier through which fish cannot escape. Globally, seine nets catch around 25 million tonnes of fish each year, mainly through the use of purse seines in large scale pelagic fisheries. In a mangrove setting they are commonly used from a beach or in estuaries and channels, and tend to be much smaller scale.				
Beach seine	Beach seines are seine nets operated from the shore. They are generally hauled by hand, requiring at least two people. Often larger numbers of people work together to haul larger nets, and a small boat may be used for net setting.	Small scale	Finfish	Beaches, adjacent to or below mangroves	Seines, like most net-based techniques, have the potential to cause bycatch of unwanted species. Depending on mesh size, they may also catch undersized individuals
Channel seine	Similar to a beach seine, this technique involves hand-hauling a seine net. However, the net is pulled along a channel rather than in to a beach.	Small scale	Finfish, prawn larvae	Mangrove channels	As for beach seines
Trawls	Trawling is an active fishing method involving dragging a net through the water behind a moving boat. It includes bottom trawling, where the net is dragged along the sea bed, and midwater trawling. Each type of trawling catches about 15 million tonnes per year annually, making trawling the most important commercial fishing method in coastal waters. Trawls are used offshore from mangroves to catch adults of species that use the mangroves as juveniles, particularly penaeid prawns.				
Bottom trawling	Bottom trawling uses a net towed behind a boat that drags along the sea bed, catching benthic species. Typically, the net is held open by two timber or metal boards called trawl doors. The front of the net often has a heavy chain which stirs up the bottom, encouraging benthic species to swim up so that they will be caught in the net.	Large scale	Penaeid prawns	Offshore	The main sustainability concern related to bottom trawling is the damage it causes to benthic communities, destroying slow-growing, structure forming organisms such as corals. Bycatch is also a concern, although this can be partially remedied through the use of bycatch exclusion devices and square-mesh nets
Lift nets	Lift nets are submerged, then raised vertically upwards catching any fish or other species that are in the water column above them. Fish may be attracted using bait or lights. In some places they are used in commercial fisheries, notably the Caspian Sea. In mangroves, however, lift nets are used in small scale fisheries, usually by a single fisherman hauling the net by hand.				

Portable lift nets	These usually include a net on a square frame, with ropes attached at the corners so that it can be lowered into the water with the net remaining horizontal. The ropes are generally attached to a long stick, which is used as lever to lower and raise the net.	Small scale	Finfish, prawn larvae	Mangrove channels, rivers, outside mangrove	Lift net fisheries are generally small-scale with few sustainability concerns. Nets used may have fine meshes leading to some bycatch, but much of this can be quickly released back into the water.
Falling gear	This includes any gear which falls onto fish from above. The only example applicable to mangrove systems is cast nets.				
Cast nets	Cast nets are circular nets with a weighted line around the perimeter, which enables the net to be thrown over a shoal of fish. Lines attached to the weighted edge of the net are then retrieved through a hole in the centre, closing the net around the fish.	Small scale	Finfish	Mangrove channels, pools etc.	Cast nets are targeted at a specific shoal of fish, meaning the potential for bycatch is relatively low. The method is used to catch small fish, which may not yet have reproduced. This could deplete stocks if fishing pressure is high.
Gillnets and entangling nets	This category includes all nets that entangle fish or other fishery species in their mesh. This is one of the most widely used fishing gears, catching between five and 10 million tonnes annually. Much of this comes from large scale pelagic drift net fisheries, but entangling nets are also widely used in small scale fisheries. As a passive gear type, there are concerns over "ghost fishing", where lost or discarded nets continue to catch and kill marine life, sometimes for many years.				
Set gillnets	Gillnets catch fish by allowing them to pass partially through the net. They are unable to escape backwards due to the mesh catching behind the gill covers, hence the name. Gill nets are suspended vertically in the water column using floats at the top and weights at the base. Set gillnets are anchored in position.	Small-medium scale	Finfish	Mangrove channels, outside mangroves	Gill nets are size-selective, allowing a specific size class of fish to be targeted. Targeting of immature fish is still possible, but means that larger fish will not be caught. In mangroves, gillnets can be set across channels, giving high catches but with a significant risk of depleting stocks, at least on a local scale.
Drift nets	Drift nets are gillnets that are not anchored. In pelagic fisheries they may be many kilometers long, but in a mangrove context they are usually 10s to 100s of meters long, and are used offshore from the mangroves from a small boat.	Small-medium scale	Finfish	Outside mangrove	As for set gillnets. Additionally, drift nets have a higher chance of being lost, leading to ghost fishing. They may also have a greater risk of bycatch of cetaceans, sharks and other non-target species which are not present in the channels where set gillnets are used.

Trammel nets	Trammel nets have three layers of netting, one fine mesh layer sandwiched between two large meshed nets. The fine middle mesh is slack, so that a fish hitting it will push a section of it through the large mesh on the other side, forming a pocket in which the fish is caught. Like gillnets, they are set vertically in the water column, and are often anchored on or near the bottom.	Small-medium scale	Finfish, crabs, prawns	Mangrove channels, outside mangroves	Trammel nets are less size selective than gillnets, increasing the risk of bycatch of undersized fish, in addition to the potential bycatch of larger non-target species. Like gillnets, they are also responsible for ghost fishing if gear is lost, although their use as anchored nets makes this less likely.
Traps	Traps are gear that fish or crustaceans are able to enter, but unable or unlikely to exit. They often use funnel-like entrances with a large external aperture and a small internal one. They may be baited, or they may use the flow of water to encourage target species to enter. They have limited importance in terms of tonnage of global catch, but in the small to medium scale fisheries where they are commonly used they are one of the main catch methods, particularly for use within the mangroves.				
Pound nets	Pound nets are nets are fish traps with net floors and walls which run from the bottom to the surface. Fish are directed to a gap in the wall by long lines of netting which form a V shape leading to the trap. The top of the net is open, and fish are harvested either by hauling in the net or using a scoop net. They are set in shallow areas with fast-flowing water which push fish into the net, and may be a semi-permanent installation.	Small-medium scale	Finfish, prawn larvae. Especially species that migrate with the tide.	Mangrove channels, shallow rivers.	Catch of undersized individuals or undesirable species is potentially a problem, depending on the mesh size used. Unlike with nets that are hauled onto a boat, however, it is often possible to release this bycatch alive and undamaged.
Fyke nest	Fyke nets are similar to pound nets, but instead of running from the bottom to the surface they have a cylindrical net, into which fish are guided by long wings. They are fixed in position with anchors or stakes, and catch fish swimming on the bottom.	Small-medium scale	Finfish, prawn larvae	Mangrove channels, shallow rivers.	As for pound nets. As fyke nets are set underwater, they have to be hauled out for fish to be harvested, potentially increase the risk of bycatch being injured.
Stow nets	Stow nets are simple bag or cone-shaped nets that are fixed in position in areas of strong current, such as river estuaries. They may have a frame to hold the mouth of the net open. They act as filters, catching any organism that is swept into them. To harvest the catch, the end of the net is brought aboard a boat and opened, leaving the rest of the net in place.	Small-medium scale	Finfish, prawn larvae	River estuaries, fast flowing channels	Stow nets often use fine meshes, leading to catches of undersized individuals, potentially damaging populations. Stow nets are one of the main ways of catching prawn larvae for aquaculture, and up to 90% of the catch may be discarded.

Barriers, fences, weirs, corrals etc	These methods use permanent or semi-permanent installations. They may work similarly to pound and fyke nets with walls directing fish into an enclosure, or they may rely on the falling tide leaving fish stranded inside a wall or fence.	Small-medium scale	Finfish, prawns, crabs	Shallow, tidal waters	Like pound nets, there is a risk of bycatch but often these may be returned to the water alive, or allowed to remain in the enclosure until the tide rises again.
Pots	Pots are one of the main methods use to catch crustaceans, but may also be used to catch fish and cephalopods. They are essentially a cage or basket with one or more funnel-shaped entrances or internal baffles. These provide an easy entry into the pot, but only a small hole for the exit. Pots are usually baited to entice target species to enter.	Small-large scale	Crabs, lobsters, cephalopods, finfish	Mostly within mangroves and channels, but also used offshore.	Bycatch of undersized individuals is a potential issue, as is ghost fishing by lost pots. These can be mitigated by escape panels that allow small individuals to leave the pot, and by biodegradable materials that limit ghost-fishing time.
Hooks and lines	Hooks and lines are another main fishing method, catching over 5 million tonnes of fish per year globally. Much of this catch comes from commercial fisheries for pelagic species such as tuna, but hooks and lines are common in fisheries of all scales around the world. They are also the main method employed by recreational fishers.				
Handlines and pole-lines	This includes various different forms of hook and line fishing. Lines may be handheld, or attached to a pole or rod. The bait may be a natural or artificial food of the target species, presented on the bottom or suspended from a float, or it may be a synthetic lure, moved through the water to mimic a prey item.	Used at all scales, and in recreational fisheries.	Primarily finfish	Used in all locations	Hook and line fishing is one of the less environmentally damaging techniques. Hook and bait size can be adjusted to target specific species and size classes. There is some potential for bycatch of unwanted species, and lost hooks can remain lodged in fish.
Set lines	These are lines, usually with multiple baited hooks, that are fixed in place for a period of time, then retrieved with any fish caught on the hooks.	Small-medium scale	Primarily finfish	Within or close to mangroves	As with hand and pole-lines, there is potential for bycatch. In addition, the unattended nature of set lines means that bycatch is more likely to be dead before it can be released.
Grappling and wounding	Harpoons, spears and bows and arrows are all used as fishing techniques. They are often used by indigenous people as a traditional form of fishing, and are also used in recreational fisheries. They may be used from land, for example at channel edges within the mangroves, or in the water by snorkelling or scuba diving. As they allow single individuals to be targeted, they have little environmental impact beyond the taking of those individuals.				
Hand collecting	Hand collecting is ubiquitous in small-scale fisheries around the world. It is particularly common for animals that live in the intertidal zone and can be collected on land at low tide. Examples include bivalve molluscs and some crab species. Techniques vary and can be highly specialised - see the section on the mangrove crab *Ucides cordatus* fishery for examples.				

REFERENCES

Aburto-Oropeza, O., E. Ezcurra, G. Danemann, V. Valdez, J. Murray, and E. Sala. 2008. Mangroves in the Gulf of California increase fishery yields. Proceedings of the National Academy of Sciences 105(30):10456–10459.

Ahmed, N., and M. Troell. 2010. Fishing for prawn larvae in Bangladesh: an important coastal livelihood causing negative effects on the environment. Ambio 39(1):20–29.

Alongi, D. M. 1994. Zonation and seasonality of benthic primary production and community respiration in tropical mangrove forests. Oecologia 98(3-4):320–327.

Alongi, D. M. 2009. The energetics of mangrove forests. Springer Verlag, New York.

Amarasinghe, U. S., M. D. Amarasinghe, and C. Nissanka. 2002. Investigation of the Negombo estuary (Sri Lanka) brush park fishery, with an emphasis on community-based management. Fisheries Management and Ecology 9(1):41–56.

Appeldoorn, R. S. 1997. The fisheries for the queen conch, *Strombus gigas*, mangrove oyster, *Crassostrea rhizophorae*, and other shelled mollusks of Puerto Rico. NOAA Technical Report NMFS 0:223–234.

Ault, J. S., R. Humston, M. F. Larkin, E. Perusquia, N. A. Farmer, J. Luo, N. Zurcher, S. G. Smith, L. R. Barbieri, and J. M. Posada. 2010. Population Dynamics and Resource Ecology of Atlantic Tarpon and Bonefish. Pages 217–258 Biology and Management of the World Tarpon and Bonefish Fisheries.

Baluyut, E. A. 1989. Aquaculture systems and practices: a selected review. Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations, Rome, Italy.

Barnes-Mauthe, M., K. L. L. Oleson, and B. Zafindrasilivonona. 2013. The total economic value of small-scale fisheries with a characterization of post-landing trends: An application in Madagascar with global relevance. Fisheries Research 147:175–185.

Beck, M. W., K. L. Heck, K. W. Able, D. L. Childers, D. B. Eggleston, B. M. Gillanders, B. Halpern, C. G. Hays, K. Hoshino, T. J. Minello, R. J. Orth, P. F. Sheridan, and M. P. Weinstein. 2001. The Identification, Conservation, and Management of Estuarine and Marine Nurseries for Fish and Invertebrates. BioScience 51(8):633–641.

Beitl, C. M. 2011. Cockles in custody: The role of common property arrangements in the ecological sustainability of mangrove fisheries on the Ecuadorian coast. International Journal of the Commons 5:485–512.

De Boer, W. F., A. F. Blijdenstein, and F. Longamane. 2002. Prey choice and habitat use of people exploiting intertidal resources. Environmental Conservation 29:238–252.

De Boer, W. F., A. M. P. van Schie, D. F. Jocene, A. B. P. Mabote, and A. Guissamulo. 2001. The impact of artisanal fishery on a tropical intertidal benthic fish community. Environmental Biology of Fishes 61:213–229.

Bologna, P. a. X. 2014. Mangrove loss leads to fish hyperutilization of seagrass beds in a UNESCO biosphere reserve. Journal of Fish Biology 84(5):1620–1625.

Bosire, J. O., F. Dahdouh-Guebas, M. Walton, B. I. Crona, R. R. Lewis III, C. Field, J. G. Kairo, and N. Koedam. 2008. Functionality of restored mangroves: A review. Aquatic Botany 89(2):251–259.

Buitrago, E., and D. Alvarado. 2005. A highly efficient oyster spat collector made with recycled materials. Aquacultural Engineering 33:63–72.

Camilleri, J. 1989. Leaf choice by crustaceans in a mangrove forest in Queensland. Marine Biology 102(4):453–459.

Capistrano, J., and P. Lopes. 2012. Crab gatherers perceive concrete changes in the life history traits of *Ucides cordatus* (Linnaeus, 1763), but overestimate their past and current catches. Ethnobiology and Conservation 1(0).

Chong, V. C., A. Sasekumar, M. U. C. Leh, and R. D'Cruz. 1990. The fish and prawn communities of a Malaysian coastal mangrove system, with comparisons to adjacent mud flats and inshore waters. Estuarine, Coastal and Shelf Science 31(5):703–722.

Cocheret de la Morinière, E., B. J. A. Pollux, I. Nagelkerken, and G. van der Velde. 2003. Diet shifts of Caribbean grunts (Haemulidae) and snappers (Lutjanidae) and the relation with nursery-to-coral reef migrations. Estuarine, Coastal and Shelf Science 57(5–6):1079–1089.

Costa, H. H., and M. J. S. Wijeyaratne. 1994. Utilization of mangrove species in brushpark construction and their effects on Negombo Estuary fishery

(Sri Lanka). Journal of Applied Ichthyology 10(2-3):96–103.

Danylchuk, A., S. Danylchuk, D. P. Philipp, T. L. Goldberg, S. J. Cooke, and J. Koppelman. 2007a. Ecology and Management of Bonefish (*Albula* spp.) in the Bahamian Archipelago. Pages 79–92 Biology and Management of the World Tarpon and Bonefish Fisheries. CRC Press.

Danylchuk, S. E., A. J. Danylchuk, S. J. Cooke, T. L. Goldberg, J. Koppelman, and D. P. Philipp. 2007b. Effects of recreational angling on the post-release behavior and predation of bonefish (*Albula vulpes*): The role of equilibrium status at the time of release. Journal of Experimental Marine Biology and Ecology 346(1–2):127–133.

Dawes, C. 1999. Mangrove structure, litter and macroalgal productivity in a northern- most forest of Florida. Mangroves and Salt Marshes 3(4):259–267.

Department of Fisheries Western Australia. 2014. Barramundi recreational fishing. http://www.fish.wa.gov.au/Species/Barramundi/Pages/Barramundi-Recreational-Fishing.aspx.

Diele, K., V. Koch, and U. Saint-Paul. 2005. Population structure, catch composition and CPUE of the artisanally harvested mangrove crab *Ucides cordatus* (Ocypodidae) in the Caeté estuary, North Brazil: Indications for overfishing? Aquatic Living Resources 18:169–178.

Dittel, A. I., C. E. Epifanio, L. A. Cifuentes, and D. L. Kirchman. 1997. Carbon and Nitrogen Sources for Shrimp Postlarvae Fed Natural Diets from a Tropical Mangrove System. Estuarine, Coastal and Shelf Science 45(5):629–637.

Ewel, K. C. 2008. Mangrove crab (*Scylla serrata*) populations may sometimes be best managed locally. Journal of Sea Research 59(1–2):114–120.

FAO. 2011. FishStatJ: Universal software for fishery statistical time series. FAO Fisheries and Aquaculture Department, Statistics and Information Service.

FAO. 2012. The state of world fisheries and aquaculture. Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 2014. Species Fact Sheets: *Anadara granosa*. Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, and World Fish Centre. 2008. Small- scale capture fisheries – a global overview with emphasis on developing countries: a preliminary report of the Big Numbers Project.

Fedler, A. J., and C. Hayes. 2008. Economic impact of recreational fishing for bonefish, permit and tarpon in Belize for 2007. Gainesville: Friends of Turneffe Atoll.

Fedler, T. 2010. The economic impact of flats fishing in The Bahamas. The Bahamian Flats Fishing Alliance.

Giri, C., E. Ochieng, L. L. Tieszen, Z. Zhu, A. Singh, T. Loveland, J. Masek, and N. Duke. 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. Global Ecology and Biogeography 20(1):154–159.

Golbuu, Y., S. Victor, E. Wolanski, and R. H. Richmond. 2003. Trapping of fine sediment in a semi-enclosed bay, Palau, Micronesia. Estuarine, Coastal and Shelf Science 57(5–6):941–949.

De Groot, R., L. Brander, S. van der Ploeg, R. Costanza, F. Bernard, L. Braat, M. Christie, N. Crossman, A. Ghermandi, L. Hein, S. Hussain, P. Kumar, A. McVittie, R. Portela, L. C. Rodriguez, P. ten Brink, and P. van Beukering. 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosystem Services 1(1):50–61.

Grubert, M., M. Leslie, and M. Winning. 2012. Mud Crab *Scylla serrata*, *Scylla olivacea*. Pages 131–127 *in* M. Flood, I. Stobutzki, J. Andrews, G. Begg, W. Fletcher, C. Gardner, J. Kemp, A. Moore, A. O'Brien, and R. Quinn, editors. Status of key Australian fish stocks reports 2012. Fisheries Research and Development Corporation, Canberra.

Gupta, H., S.-J. Kao, and M. Dai. 2012. The role of mega dams in reducing sediment fluxes: A case study of large Asian rivers. Journal of Hydrology 464–465:447–458.

Hamilton, L. S., and S. C. Snedaker. 1984. Handbook for Mangrove Area Management. UNEP and East West Center, Environment and Policy Institute, Honolulu.

Harrison, P. J., N. Khan, K. Yin, M. Saleem, N. Bano, M. Nisa, S. I. Ahmed, N. Rizvi, and F. Azam. 1997. Nutrient and phytoplankton dynamics in two mangrove tidal creeks of the Indus River delta, Pakistan. Marine Ecology Progress Series 157:13–19.

Hemminga, M., F. Slim, J. Kazungu, G. Ganssen, J. Nieuwenhuize, and N. Kruyt. 1994. Carbon outwelling from a mangrove forest with adjacent seagrass beds and coral reefs (Gazi

Bay, Kenya). Marine Ecology-Progress Series 106:291–291.

Hill, B. J. 1994. Offshore spawning by the portunid crab *Scylla serrata* (Crustacea: Decapoda). Marine Biology 120(3):379–384.

Hutchison, J., A. Manica, R. Swetnam, A. Balmford, and M. Spalding. 2014. Predicting global patterns in mangrove forest biomass. Conservation Letters 7(3):233–240.

Islam, M. S., and K. Ikejima. 2010. Gear type, species composition and economic value of fisheries in the mangroves of Pak Phanang, Thailand. Wetlands Ecology and Management 18:27–36.

Ivo, C. T. C., A. F. Dias, and R. I. Mota. 1999. Study on the biology of the mangrove crab *Ucides cordatus cordatus*, (Linnaeus, 1763) caught at Parnaibo river delta, Piaui state. Boletim Tecnico Cientifico do CEPENE 7:53–84.

Jana, H., K. C. Mondal, C. Maity, K. Ghosh, A. Mitra, K. Banerjee, S. Dey, and B. R. Pati. 2013. Variation of antioxidant biomarkers in the edible oyster *Saccostrea cucullata* collected from three different water bodies of Sundarbans. Chemistry and Ecology 29(8):745–753.

Jelbart, J. E., P. M. Ross, and R. M. Connolly. 2007. Fish assemblages in seagrass beds are influenced by the proximity of mangrove forests. Marine Biology 150(5):993–1002.

Jennerjahn, T., and V. Ittekkot. 2002. Relevance of mangroves for the production and deposition of organic matter along tropical continental margins. Naturwissenschaften 89(1):23–30.

Johnston, D., N. V. Trong, T. T. Tuan, and T. T. Xuan. 2000. Shrimp seed recruitment in mixed shrimp and mangrove forestry farms in Ca Mau Province, Southern Vietnam. Aquaculture 184:89–104.

Kelleher, K. 2005. Discards in the World's Marine Fisheries An Update. Food and Agriculture Organization of the United Nations, Rome, Italy.

Kimirei, I. A., I. Nagelkerken, Y. D. Mgaya, and C. M. Huijbers. 2013. The Mangrove Nursery Paradigm Revisited: Otolith Stable Isotopes Support Nursery-to-Reef Movements by Indo-Pacific Fishes. PLoS ONE 8(6):e66320.

Kosuge, T. 2001. Brief assessment of stock of mud crabs *Scylla* spp. in Matang Mangrove Forest, Malaysia and proposal for resources management. Japan Agricultural Research Quarterly 35(2):145–148.

Kristensen, E., S. Bouillon, T. Dittmar, and C. Marchand. 2008. Organic carbon dynamics in mangrove ecosystems: A review. Aquatic Botany 89(2):201–219.

Laegdsgaard, P., and C. Johnson. 2001. Why do juvenile fish utilise mangrove habitats? Journal of Experimental Marine Biology and Ecology 257(2):229–253.

Lapègue, S., I. Boutet, A. Leitão, S. Heurtebise, P. Garcia, C. Thiriot-Quiévreux, and P. Boudry. 2002. Trans-Atlantic Distribution of a Mangrove Oyster Species Revealed by 16S mtDNA and Karyological Analyses. The Biological Bulletin 202(3):232–242.

Lee, S. Y. 1998. Ecological role of grapsid crabs in mangrove ecosystems: a review. Marine and Freshwater Research 49(4):335–343.

Lee, S. Y. 2004. Relationship between mangrove abundance and tropical prawn production: a re-evaluation. Marine Biology 145(5):943–949.

Lewis III, R. R., and B. Brown. 2014. Ecological mangrove rehabilitation – a field manual for practitioners. Mangrove Action Project, Canadian International Development Agency, and OXFAM.

Lin, G., T. Banks, and L. da S. L. O. Sternberg. 1991. Variation in δ13C values for the seagrass *Thalassia testudinum* and its relations to mangrove carbon. Aquatic Botany 40(4):333–341.

Lucero, C., J. Cantera, and R. Nelra. 2012. The fisheries and growth of ark clams (arcoida: Arcidae) Anadara tuberculosa in Málaga Bay, Colombian Pacific, 2005-2007. Pesquería y crecimiento de la piangua (arcoida: Arcidae) *Anadara tuberculosa* en la Bahía de Málaga del Pacífico Colombiano, 2005-2007 60:203–217.

Lugendo, B. R., A. Pronker, I. Cornelissen, A. de Groene, I. Nagelkerken, M. Dorenbosch, G. van der Velde, and Y. D. Mgaya. 2005. Habitat utilisation by juveniles of commercially important fish species in a marine embayment in Zanzibar, Tanzania. Aquatic Living Resources 18(02):149–158.

Mackenzie, C. L. 2001. The fisheries for mangrove cockles, *Anadara* spp., from Mexico to Peru, with descriptions of their habitats and biology, the fishermen's lives, and the effects of shrimp farming. U S National Marine Fisheries Service Marine Fisheries Review 63:1–39.

Mackenzie, C. L. 2005. The commercial oysters of the Gulf of Mexico and the Caribbean Sea: ecology, biology, and fisheries. Proceedings of the Gulf and Caribbean Fisheries Institute 56:521–535.

Manson, F. J., N. R. Loneragan, G. A. Skilleter, and S. R. Phinn. 2005. An evaluation of the evidence for linkages between mangroves and fisheries: a synthesis of the literature and identification of research directions. Oceanography and Marine Biology: An Annual Review 43:483–513.

Marine Stewardship Council. 2013. MSC Certification Requirements V1.3. http://www.msc.org/documents/scheme-documents/msc-scheme-requirements/msc-certification-requirements/at_download/file.

Martosubroto, P., and N. Naamin. 1977. Relationship between tidal forests (mangroves) and commercial shrimp production in Indonesia. Marine Research in Indonesia 18(8):1–86.

Maunder, M. N., and A. E. Punt. 2004. Standardizing catch and effort data: a review of recent approaches. Fisheries Research 70(2–3):141–159.

Mazda, Y., M. Magi, Y. Ikeda, T. Kurokawa, and T. Asano. 2006. Wave reduction in a mangrove forest dominated by *Sonneratia* sp. Wetlands Ecology and Management 14(4):365–378.

McIvor, C. C., and T. J. Smith III. 1995. Differences in the Crab Fauna of Mangrove Areas at a Southwest Florida and a Northeast Australia Location: Implications for Leaf Litter Processing. Estuaries 18(4):591–597.

McKinnon, A. D., L. A. Trott, D. M. Alongi, and A. Davidson. 2002. Water column production and nutrient characteristics in mangrove creeks receiving shrimp farm effluent. Aquaculture Research 33(1):55–73.

McMahon, K. W., M. L. Berumen, I. Mateo, T. S. Elsdon, and S. R. Thorrold. 2011. Carbon isotopes in otolith amino acids identify residency of juvenile snapper (Family: Lutjanidae) in coastal nurseries. Coral Reefs 30(4):1135–1145.

Meager, J. J., I. Williamson, N. R. Loneragan, and D. J. Vance. 2005. Habitat selection of juvenile banana prawns, *Penaeus merguiensis* de Man: Testing the roles of habitat structure, predators, light phase and prawn size. Journal of Experimental Marine Biology and Ecology 324(2):89–98.

Mendonca, J. T., and I. C. Machado. 2010. Mangrove oyster (*Crassostrea* spp.) (Sacco, 1897) extractivism in Cananeia estuary (Sao Paulo, Brazil) from 1999 to 2006: capture and management evaluation. Brazilian Journal of Biology 70:65–73.

Meynecke, J.-O., S. Y. Lee, N. C. Duke, and J. Warnken. 2006. Effect of rainfall as a component of climate change on estuarine fish production in Queensland, Australia. Estuarine, Coastal and Shelf Science 69(3–4):491–504.

Micheli, F. 1993. Feeding ecology of mangrove crabs in North Eastern Australia: mangrove litter consumption by *Sesarma messa* and *Sesarma smithii*. Journal of Experimental Marine Biology and Ecology 171(2):165–186.

Mumby, P. J., A. J. Edwards, J. Ernesto Arias-Gonzalez, K. C. Lindeman, P. G. Blackwell, A. Gall, M. I. Gorczynska, A. R. Harborne, C. L. Pescod, H. Renken, C. C. C. Wabnitz, and G. Llewellyn. 2004. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. Nature 427(6974):533–536.

Nagelkerken, I., S. J. M. Blaber, S. Bouillon, P. Green, M. Haywood, L. G. Kirton, J.-O. Meynecke, J. Pawlik, H. M. Penrose, A. Sasekumar, and P. J. Somerfield. 2008. The habitat function of mangroves for terrestrial and marine fauna: A review. Aquatic Botany 89(2):155–185.

Nagelkerken, I., S. Kleijnen, T. Klop, R. A. C. J. van den Brand, E. C. de la Morinire, and G. van der Velde. 2001. Dependence of Caribbean reef fishes on mangroves and seagrass beds as nursery habitats: a comparison of fish faunas between bays with and without mangroves/seagrass beds. Marine Ecology Progress Series 214:225–235.

Nagelkerken, I., G. van der Velde, M. W. Gorissen, G. J. Meijer, T. Van't Hof, and C. den Hartog. 2000. Importance of Mangroves, Seagrass Beds and the Shallow Coral Reef as a Nursery for Important Coral Reef Fishes, Using a Visual Census Technique. Estuarine, Coastal and Shelf Science 51(1):31–44.

Nascimento, D. M., E. N. Ferreira, D. M. M. S. Q. Bezerra, P. D. Rocha, R. R. N. Alves, and J. S. Mourão. 2012. Capture techniques' use of caranguejo-uçá crabs (*Ucides cordatus*) in Paraíba state (northeastern Brazil) and its socio-environmental implications. Anais Da Academia Brasileira De Ciencias 84:1051–1064.

Newell, S. Y. 1996. Established and potential impacts of eukaryotic mycelial decomposers in marine/terrestrial ecotones. Journal of Experimental Marine Biology and Ecology 200(1–2):187–206.

Nordhaus, I., M. Wolff, and K. Diele. 2006. Litter processing and population food intake of the mangrove crab *Ucides cordatus* in a high intertidal forest in northern Brazil. Estuarine, Coastal and Shelf Science 67(1–2):239–250.

Nordi, N., A. K. Nishida, and R. R. N. Alves. 2009. Effectiveness of Two Gathering Techniques for *Ucides cordatus* in Northeast Brazil: Implications for the Sustainability of Mangrove Ecosystems. Human Ecology 37:121–127.

Nuruzzaman, M. 2002. Status of the shrimp hatchery and nursery operations in Bangladesh. Shrimp and Coastal Aquaculture Component, Fourth Fisheries Project.

O'Donohue, M. J. H., and W. C. Dennison. 1997. Phytoplankton Productivity Response to Nutrient Concentrations, Light Availability and Temperature along an Australian Estuarine Gradient. Estuaries 20(3):521–533.

Oliveira-Neto, J. F., W. A. Boeger, M. R. Pie, A. Ostrensky, and D. B. Hungria. 2007. Genetic structure of populations of the mangrove crab *Ucides cordatus* (Decapoda: Ocypodidae) at local and regional scales. Hydrobiologia 583(1):69–76.

Ostrom, E. 1990. Governing the commons: The evolution of institutions for collective action. Cambridge university press.

Paw, J. N., and T.-E. Chua. 1991. An assessment of the ecological and economic impact of mangrove conversion in Southeast Asia. Towards an integrated management of tropical coastal resources. ICLARM Conference Proceedings 22:201–212.

Potter, I., J. Penn, and K. Brooker. 1986. Life cycle of the western school prawn, *Metapenaeus dalli* Racek, in a Western Australian estuary. Marine and Freshwater Research 37(1):95–103.

Primavera, J. H. 1998. Mangroves as Nurseries: Shrimp Populations in Mangrove and Non-mangrove Habitats. Estuarine, Coastal and Shelf Science 46(3):457–464.

Rahman, M. M. 2001. The Impact of Shrimp Trawling Fisheries on Living Marine Resources of Bangladesh. In: Tropical Shrimp Fisheries and Their Impact on Living Resources. Food and Agriculture Organization of the United Nations, Rome, Italy.

Robertson, A. I., and P. A. Daniel. 1989a. Decomposition and the annual flux of detritus from fallen timber in tropical mangrove forests. Limnology and Oceanography 34(3):640–646.

Robertson, A. I., and P. A. Daniel. 1989b. The influence of crabs on litter processing in high intertidal mangrove forests in tropical Australia. Oecologia 78(2):191–198.

Robertson, A. I., and N. C. Duke. 1987. Mangroves as nursery sites: comparisons of the abundance and species composition of fish and crustaceans in mangroves and other nearshore habitats in tropical Australia. Marine Biology 96(2):193–205.

Rönnbäck, P. 1999. The ecological basis for economic value of seafood production supported by mangrove ecosystems. Ecological Economics 29(2):235–252.

Rönnbäck, P., M. Troell, N. Kautsky, and J. H. Primavera. 1999. Distribution Pattern of Shrimps and Fish Among *Avicennia* and *Rhizophora* Microhabitats in the Pagbilao Mangroves, Philippines. Estuarine, Coastal and Shelf Science 48(2):223–234.

Rönnbäck, P., M. Troell, T. Zetterström, and D. E. Babu. 2003. Mangrove dependence and socio-economic concerns in shrimp hatcheries of Andhra Pradesh, India. Environmental Conservation 30:344–352.

Ruitenbeek, H. J. 1994. Modelling economy-ecology linkages in mangroves: Economic evidence for promoting conservation in Bintuni Bay, Indonesia. Ecological Economics 10(3):233–247.

Salthaug, A., and O. R. Godø. 2001. Standardisation of commercial CPUE. Fisheries Research 49(3):271–281.

Sarkar, S. K., and A. K. Bhattacharya. 2003. Conservation of biodiversity of the coastal resources of Sundarbans, Northeast India: an integrated approach through environmental education. Marine pollution bulletin 47(1-6):260–264.

Sheaves, M. 1996. Habitat-specific distributions of some fishes in a tropical estuary. Marine and Freshwater Research 47(6):827–830.

Sheaves, M., and B. Molony. 2000. Short-circuit in the mangrove food chain. Marine Ecology Progress Series 199:97–109.

Slim, F. ., M. . Hemminga, C. Ochieng, N. . Jannink, E. Cocheret de la Morinière, and G. van der Velde. 1997. Leaf litter removal by the snail *Terebralia palustris* (Linnaeus) and sesarmid crabs in an East African mangrove forest (Gazi Bay, Kenya). Journal of Experimental Marine Biology and Ecology 215(1):35–48.

Spalding, M., M. Kainuma, and L. Collins. 2010. World Atlas of Mangroves. Earthscan.

Staples, D. J., and D. S. Heales. 1991. Temperature and salinity optima for growth and survival of juvenile banana prawns *Penaeus merguiensis.* Journal of Experimental Marine Biology and Ecology 154(2):251–274.

Vakily, J. M., K. Seto, and D. Pauly. 2012. The mangrove and coastal environment of Sierra Leone. Fisheries Centre Research Reports 20:50.

Vance, D., M. Haywood, D. Heales, R. Kenyon, N. Loneragan, and R. Pendreyne. 2002. Distribution of juvenile penaeid prawns in mangrove forests in a tropical Australian estuary, with particular reference to *Penaeus merguiensis*. Marine Ecology Progress Series 228:165–177.

Vance, D. J., D. J. Staples, and J. D. Kerr. 1985. Factors affecting year-to-year variation in the catch of banana prawns (*Penaeus merguiensis*) in the Gulf of Carpentaria, Australia. Journal du Conseil 42(1):83–97.

Verweij, M. C., I. Nagelkerken, I. Hans, S. M. Ruseler, and P. R. Mason. 2008. Seagrass nurseries contribute to coral reef fish populations. Limnology and Oceanography 53(4):1540.

Victor, S., L. Neth, Y. Golbuu, E. Wolanski, and R. H. Richmond. 2006. Sedimentation in mangroves and coral reefs in a wet tropical island, Pohnpei, Micronesia. Estuarine, Coastal and Shelf Science 66(3–4):409–416.

Welcomme, R. L. 2002. An evaluation of tropical brush and vegetation park fisheries. Fisheries Management and Ecology 9(3):175–188.

Winterwerp, J. C., P. L. A. Erftemeijer, N. Suryadiputra, P. van Eijk, and L. Zhang. 2013. Defining Eco-Morphodynamic Requirements for Rehabilitating Eroding Mangrove-Mud Coasts. Wetlands 33(3):515–526.

World Bank. 2013. Fish to 2030: Prospects for fisheries and aquaculture. World Bank Group, Washington, DC.