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Data review and potential assessment approaches for mobulids in the Western and Central Pacific Ocean

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Report prepared for The Pacific Community

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EXECUTIVE SUMMARY

Mobulid rays (manta and devil rays) are pelagic elasmobranchs that are widely distributed throughout the world's oceans. Throughout their range, manta and devil rays experience substantial fishery-related mortality, both in target fisheries and also as bycatch. In view of the conservative life history of mobulid rays, there have been growing concerns about the impact of fishery mortalities on the sustainability of mobulid populations. At the same time, their extensive distribution and large-scale movement, combined with a general lack of fishery catch and landings data make population and stock assessments difficult.

Mobulid rays were designated as key shark species for assessment purposes by the Western and Central Pacific Fisheries Commission (WCPFC) in 2016. The Fifteenth Meeting of the Scientific Committee (SC15) requested further research into the stock and ecological risk status of mobulid rays, with updated information to be provided to the Scientific Committee in 2020. Specifically, the focus of the additional research was a review of available data to allow the Scientific Committee to determine the feasibility of assessing the status of mobulid rays, and the potential types of assessment approaches that may be suitable. The present project presents the outcomes of this research by providing a summary of available data from 1995 to 2018 in the context of potential assessment approaches.

In the Western and Central Pacific Ocean, there are two species of manta ray and five species of devil ray: giant manta ray *Mobula* [previously *Manta*] *birostris*, reef manta ray *M.* [previously *Manta*] *alfredi*, spinetail devil ray *M. mobular* (including *M. japanica*), longhorned pygmy devil ray *M.* [*eregoodootenkee*] *eregoodoo*, shortfin devil ray *M. kuhlii*, sicklefin devil ray *M. tarapacana* and bentfin devil ray *M. thurstoni*. Most of these species have been recorded as bycatch in purse-seine and longline fisheries in this region, with observer records including manta and devil ray captures at different taxonomic resolutions.

The analysis of observer data for the period between 1995 and 2018 highlighted distinct differences between purse-seine and longline sets, with markedly higher numbers of observed mobulid captures in purse-seine than in longline gear. The total number of observed captures was 38,034 individuals in purse seine compared with 2205 captures in longline. This difference reflects in part the considerably higher rate of observer coverage on purse-seine vessels, but also the tropical distribution of a number of mobulid species.

For both fishing gears, the taxonomic resolution of bycatch records was low until the mid-2000s, with early observer records aggregating mobulid captures as all rays or as manta and devil rays combined. Capture records at higher taxonomic resolutions were almost exclusively at the species level for manta ray in both gear types, compared with the predominantly generic reporting of devil rays that persisted including in recent years. Amongst the devil rays, spinetail devil ray, the largest in this group, was the species with the highest frequency of species-level classification. The scarcity of species-level records for smaller species of devil ray indicates the lack of observer training for distinguishing features other than size.

Observed capture rates of both manta and devil rays showed some fluctuations over time, and a clear signal of increased reporting. This signal occurred in the later part of the study period as the taxonomic resolution of the captures increased: observers first started reporting mobulid bycatch as rays, then classified it as manta and devil rays, before identifying manta rays, and subsequently some of the devil ray captures at the species level. The average capture rate of manta rays in purse seine in the last three years of this study (2016–2018) was 45.2 individuals per thousand observed sets. For devil rays, observed captures rates in purse seine were highly variable, with an average capture rate of 35.8 individuals per thousand observed sets between 2016 and 2018. In longlines, observed capture rates for both manta rays and devil rays were variable, with an overall decrease in recent years. The average capture rate for manta and devil rays combined in the last three years was 4.2 individuals per million observed hooks.

Post-release mortality is a key parameter for quantifying the impact of fishing on mobulid populations in the Western and Central Pacific Ocean, as observer records indicated that most mobulid captures were discarded. Condition-at-release is an important variable to account for when estimating post-release mortality. There were some distinct differences between purse-seine and longline observer data regarding the collection of individual condition. In purse seine, the condition at capture was not recorded for most individuals. In longline sets, this variable was recorded for most individuals; however, in recent years, there was still a considerable proportion of individuals that were recorded as alive, but without a health classification.

Among the mobulid species captured, giant manta ray (*M. birostris*) had the most data to inform an assessment in the Western and Central Pacific Ocean. In a recent analysis of observer data from the Inter-American Tropical Tuna Commission, this species was classified as the most vulnerable to fishing in the Eastern Pacific Ocean (Duffy et al. 2019). The comparative analysis also included two species of devil ray (spinetail devil ray and bentfin devil ray), highlighting that *M. birostris* should be prioritised for an assessment within the mobulid group based on data availability and also from a management perspective. The lack of a clear trend evident in the nominal catch-per-unit-effort for the giant manta ray, together with trends in reporting, prevents the implementation of a medium-data assessment in the short term. A spatial risk assessment based on a recent catch history is likely to be most suited for an assessment of this species and could be implemented immediately. Alternatives include eSAFE (Sustainability Assessment for Fishing Effects) and EASI-fish (Ecological Assessment of the Sustainable Impacts by Fisheries). Ideally, more than one approach would be trialled to increase the confidence in the resulting reference points to inform management based on fishing mortality. The assessment approach could then be upgraded to a medium-data assessment once a more extensive catch history of at least 15 years beyond the start of widespread recording is available from reconstruction.

The ongoing lack of consistent classifications of devil rays at the species level impedes the application of any assessment approach that requires catch histories. An alternative framework for assessing the vulnerability of species lacking a recent catch history is a PSA (Productivity-Susceptibility Analysis). This semi-quantitative framework ranks vulnerability to overfishing within designated species assemblages. Although it would not provide a population status for mobulids as a function of a reference point, it could assist in the prioritisation of research and observer training for the smaller species of devil ray, for which identifications at the species level remain limited. In the near future, a quantitative risk assessment such as eSAFE and EASI-fish could also be applied to spinetail devil ray *M. mobular*, as this species shows the highest frequency of reporting at the species level amongst devil rays.

While there is a range of data-poor assessment approaches that can be applied to mobulids based on the specific data availability for each species, the true status of the stock for this group will remain uncertain on the medium to long term. A management metric that could be collected and monitored for improvement is the combined implementation of safe release guidelines and the resulting condition of individuals at release. Improving these inter-related variables will have an immediate, positive impact on the survival of bycaught individuals and lower the overall fishing mortality on populations of mobulids in the WCPO.

Finally, life-history data for mobulid species occurring in the Western and Central Pacific Ocean remains generally scarce, particularly for devil rays. It might be possible to expand the scope of sampling of mobulids by observers so that key samples are collected from any dead individuals, such as the vertebrae which do not require specialized storage facilities in the short-term, and could provide valuable information on growth. Such expanded sampling would require initial consultation with observers and trainers within the Regional Observer Programme to assess feasibility across different tissue types. The Pacific Specimen Tissue Bank could serve as a repository for new mobulid samples and a point of coordination between biologists studying mobulids in the Pacific.

Recommendations

Based on the current review of data and feasibility study of potential assessment approaches for mobulid rays in the Western and Central Pacific Ocean, we make the following recommendations to the 16th Regular Session of the Scientific Committee:

- For manta ray, a quantitative risk assessment like a spatial risk assessment, eSAFE or easi-FISH should be developed in the short-term, given the relative availability of data amongst mobulids and the high risk of overfishing based on its life-history.
- For the six other species of mobulids, a semi-quantitative data-poor assessment like a Productivity Susceptibility Analysis should be considered in the short-term to prioritise resource allocation regarding their relative vulnerability to overfishing.
- For spinetail devil ray (*M. mobula*), the feasibility of a quantitative risk assessment should be considered in three to five years' time; within the devil ray group, this species was frequently identified at the species level, and is likely at risk of overfishing due to its life history.
- A metric capturing likely drivers of post-release mortality (e.g. application of safe-release guideline, condition-at-release) should be developed, collected and monitored while assessments of stock status remain uncertain.
- Tools to monitor the application of safe-release guidelines should be developed, e.g. based on amended observer forms or collection of sampling footage from e-monitoring.
- Observers should be given additional training for the identification of smaller devil ray species like *M. thurstoni*, *M. eregoodoo* and *M. tarapacana*. Special attention should be given to *M. eregoodoo*, as this species is not included in the most recent version of the species identification guide.

- Additional media should be explored to enhance the accessibility to resources in the new identification manual; potential options include a smart-phone application, identification cards and identification posters at key landing locations.

- Research into potential approaches for estimating post-release mortality of mobulids in the Western and Central Pacific Ocean should be investigated, such as the use of pop-up archival tags.

- Approaches to sample dead bycaught mobulid individuals should be investigated for use in biological studies, including the potential of the Pacific Specimen Tissue Bank to serve as repository, and point of coordination amongst mobulid biologists.

- The assumption that giant manta ray (compared with reef manta ray) dominates bycatch in tuna fisheries should be verified by DNA testing of tissue collected from bycaught individuals using non-lethal approaches.

- The extent of tangling as a cause for giant manta ray bycatch in longline gear should be documented; mitigation methods should be researched if the tangling is found to be widespread.

- Observers should be encouraged to photograph devil rays so that species identifications can be verified; a sampling programme of the collected photographs should be designed to ensure they are monitored regularly and are representative of trends within the the observer programme.

- E-monitoring options to improve species identification and assessment of individual condition at discard should be explored.

- Longline observer coverage should be increased to improve the reliability of catch reconstructions and increase the ability to characterise fleet-wide fishing impacts, particularly for rare mbulid species.

- Observers should be trained to estimate the length of bycaught individuals at a distance, including the development of a length code, based on the high number of individuals that are cut free before being brought on deck.

1. INTRODUCTION

Mobulid rays (manta and devil rays) are pelagic elasmobranchs that are widely distributed throughout the world's oceans (Lawson et al. 2017). Similar to other elasmobranch species, mobulids are characterised by late maturity, long lifespans and low reproductive output, resulting in slow population growth (see review in Couturier et al. 2012). The latter has been attributed to long gestation periods, few (usually one) offspring, and extended resting periods between pregnancies.

Manta and devil rays experience considerable fishery-related mortality throughout their range, both in target fisheries and also as bycatch (Stevens et al. 2000, Dulvy et al. 2008, Stewart et al. 2018). For example, a recent global assessment of fishery impacts on manta and devil rays documented thirteen fisheries in 12 countries that specifically target mobulids, and 30 fisheries in 23 countries that have mobulid bycatch (Croll et al. 2016). Target fisheries are usually focused on the high-value mobulid gill plates intended for Asian dried-seafood and traditional medicine markets (O'Malley et al. 2017), while bycatch records indicate significant mobulid mortality in a range of fisheries, such as longline, purse-seine and gillnet fisheries targeting tuna, swordfish and other billfish (Hall & Roman 2013, Croll et al. 2016).

In view of the conservative life history and low fecundity of mobulids, there have been growing concerns about fishing-related impacts on the sustainability of their populations. At the same time, the general lack of catch and landings data prevents the quantification of mobulid catch and bycatch across fisheries and regions. This aspect is particularly pertinent regarding species-specific information, with similarities between species making the identification of mobulid catches and distinction between species difficult and a number of species occurring sympatrically (e.g., giant and reef manta rays) (Lawson et al. 2017).

There have been a number of taxonomic changes in this group, with two recent genetic studies attempting to clarify the delineation of genera and species (White et al. 2018, Hosegood et al. 2019). The initial taxonomic revision of the Mobulidae combined the previous genus *Manta* within the single genus *Mobula* (White et al. 2018). The same revision also combined three formerly distinct species pairs, with the subsequent re-instating of one of the species (Hosegood et al. 2019, see also Notarbartolo di Sciara et al. 2020). Under the current phylogeny, the genus *Mobula* currently consists of three species of manta ray and seven species of devil ray.

Within the mobulid family, the distribution of two species of manta ray and five species of devil ray extends across the Pacific Ocean, including the region managed by the Western and Central Pacific Fisheries Commission (WCPFC) (Table 1). These mobulid species were included in a 2016 analysis of non-key shark bycatch in this region (Tremblay-Boyer & Brouwer 2016). The analysis was based on observer data from longline and purse-seine fisheries in this region, and included bycatch records of *M.* [*Manta*] *birostris*, *M. mobular* (including *M. japanica*), *M. kuhlii*, *M. tarapacana*, *M. thurstoni*, *M.* [*eregoodootenkee*] *eregoodoo*, in addition to captures that were only identified to genus and family level (Tremblay-Boyer & Brouwer 2016).

The same analysis also included a review of available data to allow the appraisal of *M. birostris* and *Mobula* spp. as potential key shark species by the WCPFC (Tremblay-Boyer & Brouwer 2016). Outcomes from the review included recommendations to designate

Table 1: Mobulid species (*Mobula* spp., manta and devil rays) that occur in the Western and Central Pacific Ocean. Species designations are based on recent taxonomic analyses (White et al. 2018, Hosegood et al. 2019, Notarbartolo di Sciara et al. 2020). Common names are as used by the International Union for Conservation of Nature and Natural Resources (IUCN), with each species' general distribution, current IUCN threat status, and the assessment year (in parentheses).

Common name	Scientific name	Distribution	IUCN status
Giant manta ray	*Mobula birostris*	Circumglobal, tropical, subtropical and temperate waters.	Vulnerable (amended 2011) (Marshall et al. 2018b).
Reef manta ray	*Mobula alfredi*	Tropical and subtropical waters of Indian and Pacific oceans.	Vulnerable (2018) (Marshall et al. 2019c).
Spinetail devil ray	*Mobula mobular* (synonym *M. japanica*)	Circumglobal, tropical, subtropical and temperate waters.	Endangered (2018) (Marshall et al. 2018a).
Longhorned pygmy devil ray	*Mobula eregoodoo* (formerly *M. eregoodootenkee*)	Northern Indian Ocean and western Pacific Ocean.	Endangered (2020) (Rigby et al. 2020a).
Shortfin devil ray	*Mobula kuhlii*	Indo-West Pacific Ocean.	Endangered (2020) (Rigby et al. 2020b).
Sicklefin devil ray	*Mobula tarapacana*	Circumglobal, tropical, subtropical and temperate waters.	Endangered (2018) (Marshall et al. 2019a).
Bentfin devil ray	*Mobula thurstoni*	Circumglobal, tropical, subtropical and temperate waters.	Endangered (2018) (Marshall et al. 2019b).

M. birostris a key shark species, and to provide additional observer training to facilitate the identification and recording of mobulid bycatch to species level. Subsequently, WCPFC13 designated mobulid species (manta and devil rays) as key shark species for assessment purposes (Clarke et al. 2017).

The 16th meeting of the WCPFC requested further research into the stock and ecological risk status of mobulid rays, with updated information to be provided to the Scientific Committee in 2020. Specifically, the focus of the additional research was a review of available data to allow the Scientific Committee to determine the feasibility of assessing the status of mobulid rays, and the potential types of assessment approaches that may be suitable.

The present project presents the outcomes of this research by providing a summary of available data in the context of potential assessment approaches "that could be used to inform of stock status, exploitation status or changes in ecological risk status as a result of fishing activities by the purse seine and long-line fleets operating in the waters under the WCPFC jurisdiction". It built on the previous analysis by Tremblay-Boyer and Brouwer (2016) by updating information from the regional observer programme, by reviewing scientific data pertaining to the biology of mobulid rays in the context of the project objectives, and by appraising potential assessment approaches for mobulid species in the Western and Central Pacific Ocean.

2. METHODS

The present research comprised of three main parts: an analysis of mobulid bycatch data from the Regional Observer Program of purse-seine and longline fleets in the Western and Central Pacific Ocean (i.e., in the WCPFC management area but also extending eastward when records are available); a review of biological and ecological data of mobulids that may be used for assessment purposes; and an appraisal of potential assessment approaches for mobulid species based on existing information as documented in the first two parts of this project. The overview of available information included data summaries and recommendations regarding the suitability of potential assessment methods.

2.1 Summary of fishery data

The full observer dataset for purse-seine and longline fleets available to The Pacific Community (SPC) was queried for the present analysis, including data from the SPC's Regional Observer Programme (ROP) and national observer programme. An extract was obtained for all records listing a mobulid species, group or family. The list of species codes included in the extract was: SRX, MAN, MNT, RMB, RMA, RMV, RMJ, RMM, RMK, RMO, RME, RMT (see Table 2), based on a search of species codes by the Food and Agricultural Organization of the United Nations (FAO) that are relevant to manta and devil rays, and including a generic ray code (SRX), which includes mobulids in its definition (**fao_codes_2020**). The analysis included the period from 1995 to 2018, from the start of the ROP to the most recent year for which observer records were considered to be complete (i.e., 2018).

Records collected by purse-seine and longline observers that were relevant to this review are key gear and attributes (including date and time, location, set type) and the species code, the fate of the mobulid catch (e.g., discarded or retained), the condition and, when available, the length and the sex of the individual, and any comments added by the observer. The quality and coverage for most variables changed over time and between programmes. For observed purse-seine sets, observers estimated the number of individuals of a given species caught from the brail net. In observed longline sets, observers recorded the species captured for every hook unless the individual escaped or was cut free before being observed. For both types of gear, individual length was measured by observers when possible. For rays, the total width (from wing tip to wing tip) is used as the standard measurement. Observer comments were surveyed to note key features but not formally catalogued.

An extract of all observer effort was also obtained to calculate total observer effort over time and space. For longline, observed effort was calculated in thousand hooks from the observed hook field submitted by observers in form LL-4. When information of observed hooks was missing, it was imputed based on the number of baskets observed. For purse seine, observed effort was calculated in thousand observed sets by counting the unique number of set identification numbers present in the observer effort extract for a given stratum.

Annual catch-per-unit-effort was calculated for each gear as the ratio of the total number of individuals observed by year (or by 2.5° cell × time-period) to the total observed effort over the same stratum.

The recent and multiple updates in phylogeny for mobulids are unlikely to have been

Table 2: Definition and scope of species codes (Food and Agricultural Organization of the United Nations) used for this analysis of observer data of mobulid ray bycatch in the Western and Central Pacific Ocean.

Code	Species	Resolution	Notes
SRX	Rays including stingrays, devil rays and manta rays	Sub-order	
MAN	Manta and devil rays	Genus	Now *Mobula* spp.
MNT	Manta rays	Species group	
RMB	*Mobula birostris*	Species	Previously *Manta birostris*
RMA	*Mobula alfredi*	Species	Previously *Manta alfredi*, not currently used by observers
RMV	*Mobula* spp.	Species group	Assumed to refer to the old definition of the *Mobula* genus and to contain devil rays only
RMM	*Mobula mobular*	Species	Not currently used by observers
RMJ	*Mobula japanica*	Species	Now *Mobula mobular*
RMK	*Mobula kuhlii*	Species	
RMO	*Mobula thurstoni*	Species	
RME	*Mobula eregoodoo*	Species	Formerly *Mobula eregoodootenkee*, not included in updated species guide (Park et al. 2019)
RMT	*Mobula tarapacana*	Species	

accounted for by observers when assigning captured individuals to a species code. A second species of manta ray (the reef manta ray, now *M. alfredi*) was recognised in 2009 (Marshall et al. 2009), and distinguished from the giant oceanic manta ray (*M. birostris*). Nevertheless, the FAO species code most frequently used to identify manta rays at the species level only recognises one manta ray species (RMB; 'giant manta ray'). The FAO species code defined for the reef manta ray has not been used by observers to date (Aurélien Panizza, SPC, *pers comm.*). Based on the nearshore distribution of reef manta ray, the current analysis assumed that all records of manta ray corresponded with giant manta ray. For this reason, all records pertaining to manta ray were considered here to belong to a single species, not a species group.

In addition, under the re-defined single genus *Mobula*, observer may use the corresponding species code RMV to classify manta ray captures. This code continues to be used frequently by observers, including in recent years. As the genus was only re-defined recently (in 2018, i.e., the last year included in the current analysis), all records under RMV were referred to as devil rays, and excluded manta rays. For clarity in the text, these records are referred to as a species group called 'devil rays' and not the generic *Mobula* spp.; however, it is worth noting that under the official FAO definition, the species code RMV corresponds with *Mobula* spp., and could (accurately) now include manta ray individuals.

Finally, as *M. mobular* and *M. japanica* were recently re-defined as conspecifics (White et al. 2018), records of the corresponding species codes RMM and RMJ were consolidated as referring to the same species, *M. mobular*.

2.2 Literature review of mobulid biology

The review of population information was focused on key biological and life-history data that would be required to inform stock assessments of mobulid species in the Western and Central Pacific Ocean. Population information was sourced *via* internet search engines (e.g., Google, Google Scholar), and included published and "grey" literature, scientific reports, and specific websites (e.g., https://www.mantatrust.org) and data bases (e.g., https://www.fishbase.se). Data sources included assessments by the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, and studies of the biology and ecology of manta and devil rays. In addition, a number of recent studies provide reviews and summaries of mobulid data, in addition to more recent species-specific research.

Population information from these different data sources was collated and summarised, providing information for each of the manta and devil ray species that occur in the Western and Central Pacific Ocean.

2.3 Appraisal of potential assessment approaches

The review of fishery bycatch data and collation of biological information was used to appraise potential assessment methods for mobulid stocks in the WCPFC region. This appraisal was conducted in view of available data for the different species, and considered different assessment approaches that may be applied accordingly based on their requirements in terms of data input and life-history information, as well as their relevance to managers.

3. RESULTS

3.1 Review of data held by the WCPFC

There were three types of data on mobulid bycatch available from data holdings of the the WCPFC: catch records, length data and condition at release. All of these data were recorded by fisheries observers, because there is no formal requirement for fishers to record mobulid bycatch in logbooks or report annual catches in catch statistics submitted to the WCPFC (Clarke et al. 2017). In addition, samples collected opportunistically (liver, stomach and muscle) from some species are held in the Pacific Specimen Bank, but their value is limited by their low sample size (typically between one and three individuals) (https://www.spc.int/ofp/PacificSpecimenBank).

3.1.1 Observed mobulid captures

The regional observer programme started in 1995, and mobulid bycatch data for purse-seine and longline gear encompassed the period from 1995 to 2018 (Figures 1 and 2). There were distinct differences between the two gear types, with markedly higher numbers of mobulid captures in purse-seine than in longline gear; total observed captures in the assessment period were 38,034 mobulid captures in purse seine compared with 2205 captures in longline. To some extent, the differences between fishing gear corresponded with the higher observer effort on purse-seine vessels.

Over time, observed captures showed an increase for both purse seine and longline, corresponding with increases in observer effort. For purse seine, observer effort increased in 2008 to a peak in 2013; although it subsequently decreased, observer effort remained comparatively high in recent years. For longline, there was a notable increase in observer effort in 2013, with relatively consistent increases since then, and the highest observer effort in 2018.

For both fishing gears, the taxonomic resolution of bycatch records was low until the mid-2000s (Figures 1 and 2). In this early part of the reporting period, observer records almost exclusively list the species codes ‘SRX’ (all rays) or ‘MAN’ (referring to both manta and devil rays; Table 2).The species code for all rays, ‘SRX’, was only used by observers on longline vessels, with a relatively high number of records assigned to this code in some years (e.g., 2003, 2006); it remained in use in recent years, including in 2018. In contrast, assignment of the generic code ‘MAN’ decreased markedly over time, with only few purse-seine and longline records assigned to this code since 2013 and 2010, respectively.

Other codes assigned to captures in both gears were general codes for manta rays and for devil rays, a species code for manta ray, and species codes for manta ray (*M. birostris*, recorded as *Manta birostris*), spinetail devil ray (*M. mobular* recorded as *M. japanica*) and sicklefin devil ray (*M. tarapacana*). In purse seine, captures also included records assigned the species code for shortfin devil ray (*M. kuhlii*), bentfin devil ray (*M. thurstoni*) and longhorned pygmy devil ray (*Mobula eregoodoo*). For years when these codes were assigned, most capture records in purse seine and longline were reported as *M. birostris* and as generic devil rays (‘RMV’). In longline, capture records also included the species code for spinetail devil ray (*M. mobular* recorded as *M. japanica*).

When considering capture records at a higher species resolution than the general MAN and SRX codes, differences in the recording of mobulid bycatch become apparent

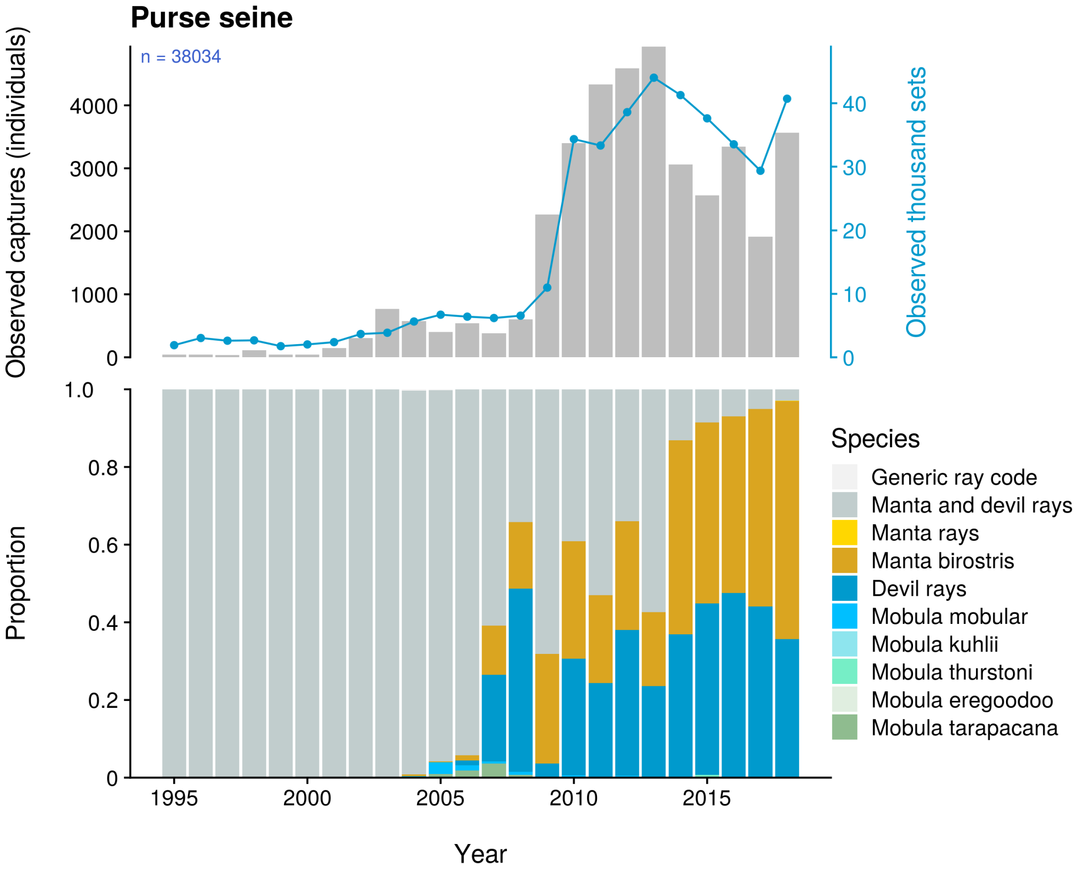

Figure 1: Top: Total annual observed captures on purse-seine sets for all manta or mobula ray individuals (grey bar), including records from the generic ray code 'SRX', with the corresponding observer effort in thousand of sets shown in the blue line. Bottom: Proportion of observed records assigned to different species codes over time. Species codes are shown unprocessed as recorded by observers and can span different taxonomic resolutions.

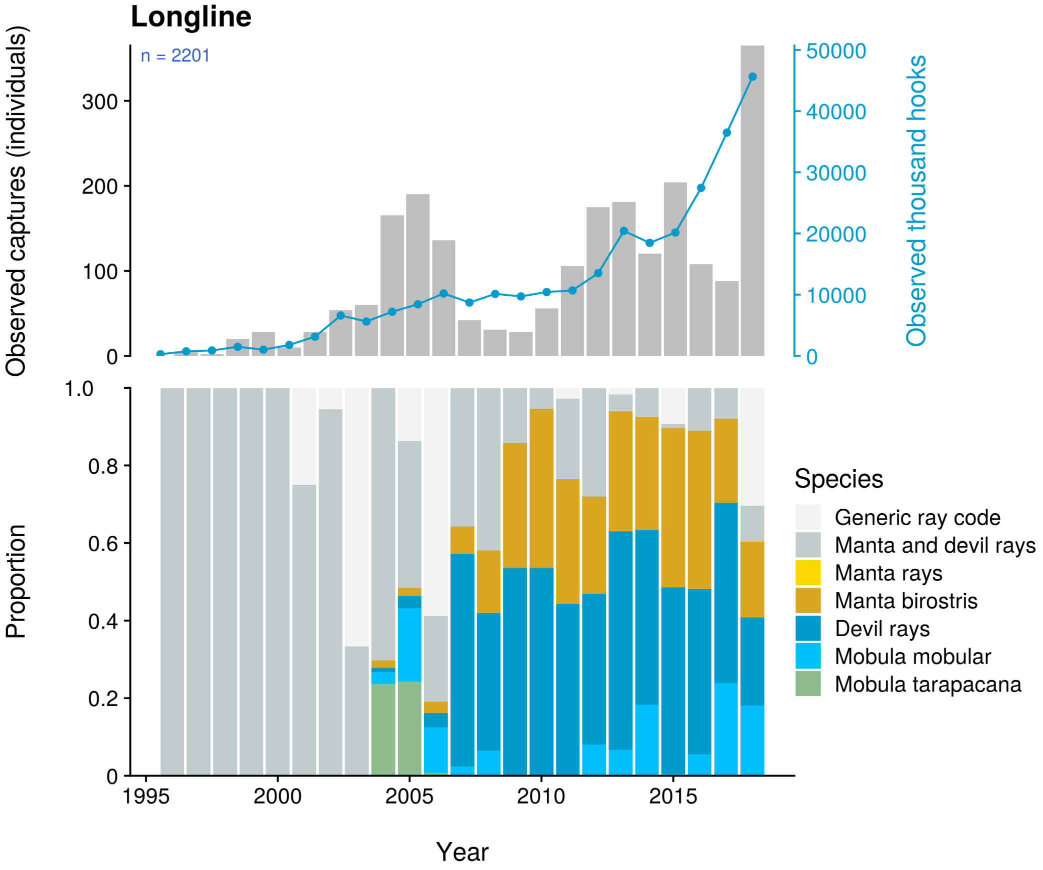

Figure 2: Top: Total annual observed captures on longline sets for all manta or mobula ray individuals (grey bar), including records from the generic ray code 'SRX', with the corresponding observer effort in thousand hooks shown in the blue line. Bottom: Proportion of observed records assigned to different species codes over time. Species codes are shown unprocessed as recorded by observers and can span different taxonomic resolutions.

between manta and devil rays (Figure 3). For manta rays, the taxonomic reporting of captures in both purse seine and longline was almost exclusively at the species level (using the code 'RMB'; *Manta birostris*). The code for the manta ray genus ('MNT'; *Manta spp.*) was rarely used, and only in recent years (i.e., 2016 to 2018). For devil rays, most captures in purse seine were assigned the generic *Mobula* species code ('RMV'). While this code was also predominantly used to record devil ray captures in longline, a number of captures were also reported with species-specific codes. In this fishing gear, the taxonomic resolution for devil rays has fluctuated over time, with distinct peaks in the use of species codes in some years, including in 2018.

In purse-seine sets, observed captures with a higher taxonomic resolution than family were generally recorded in the species grouping for devil rays or at the species level (Figure 4). At the species level, captures were predominantly reported as giant manta ray, recorded as *Manta birostris*. There were few devil ray captures reported at the species level, and these records were mostly of *M. mobular* (recorded as *M. japanica*), followed by *M. thurstoni* and *M. tarapacana* (in the earlier part of the reporting period), and also *M. kuhlii* and *M. eregoodoo* (reported as *M. eregoodootenkee*).

In longlines, the assignment of observed captures with a higher taxonomic resolution was relatively similar between the devil rays grouping and the species level (Figure 5). At the genus or species level, most captures were assigned to devil rays or to giant manta ray (recorded as *Manta birostris*). Species records of devil rays distinguished between *M. mobular* (recorded as *M. japanica*) and *M. tarapacana*, but captures of the latter species were only reported in 2004 and 2005.

For purse-seine sets, catch-per-unit-effort for manta and devil rays combined increased from 1995 to 2003, and fluctuated around 100 individuals per thousand observed sets since 2004 (Figure 6, top). For captures of manta rays recorded at the generic and the species level, capture rates increased from almost zero before 2006 (when captures were recorded at a lower taxonomic level) to a peak of 58.4 individuals per thousand observed sets in 2009 (Figure 6). Following a subsequent decline, captures rates increased again, from a low rate of of 21.4 individuals per thousand observed sets in 2013 to 53.7 individuals per thousand observed sets in 2018. The average capture rate in the last three years was 45.2 individuals per thousand observed sets.

For devil rays in purse seine, captures declared at the genus and species level were only reported from 2005 onwards (Figure 6). Capture rates were initially low in 2005 and 2006, but have been highly variable since then. The average capture rate in the last three years was 35.8 individuals per thousand sets. Capture rates for devil rays recorded at the species level were uninformative or highly variable for most species except for *M. mobular* (recorded as *M. japanica*). For *M. mobular*, capture rates declined since the species was first recorded by observers (see Appendix A, Figure A-1).

For longline sets, catch-per-unit-effort for manta and devil rays (combined) was highly variable in the first part of the assessment period (Figure 7). It showed a marked reduction in 2006, a relatively small increase up to 2012, and a subsequent decrease. The average capture rate in the last three years was 4.2 individuals per million observed hooks.

Captures of manta rays in longline sets were first identified to the generic and the species level in 2004 (Figure 3). Since then, capture rates showed notable increases over time (i.e., to 2015), as the taxonomic resolution of observed captures increased (Figure 7). Overall,

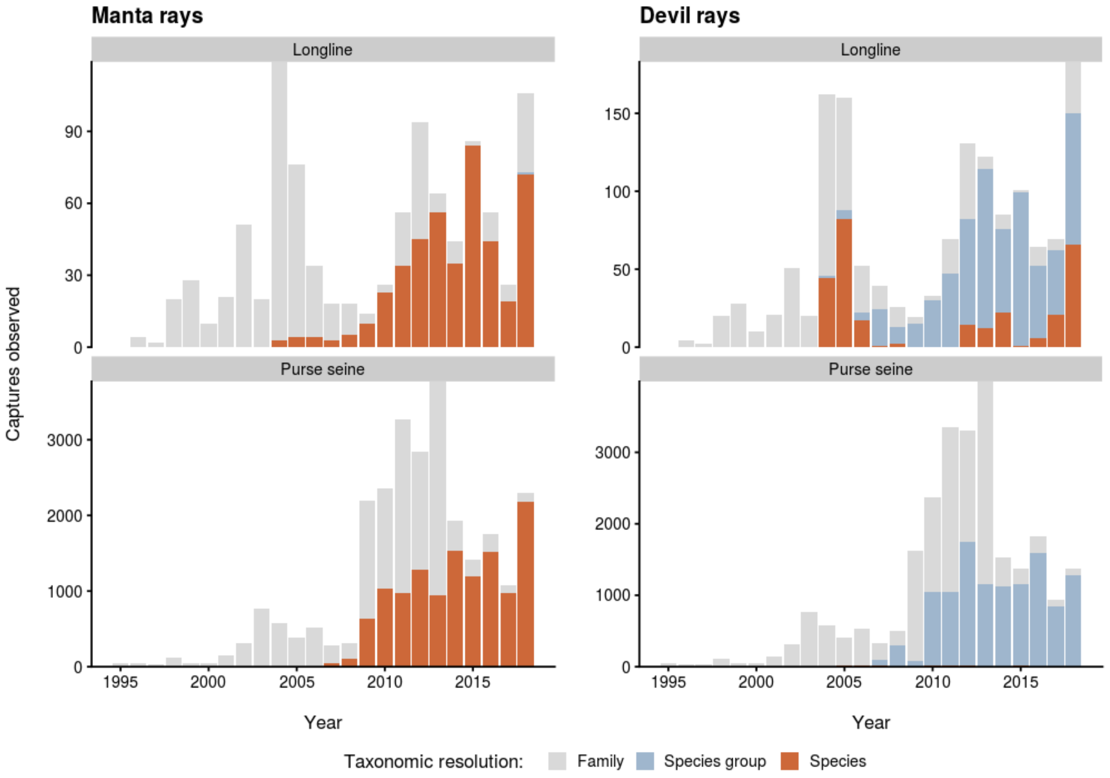

Figure 3: Taxonomic resolution of recorded species code by capture for manta rays (left) and devil rays (right), in longline (top) and purse-seine (bottom) sets, with the generic ray code 'SRX' excluded. Captures recorded at the family level (species code 'MAN') are shown in grey, at the species group level (species code 'MNT' and 'RMV' for manta and devil rays, respectively) in blue, and at the species level (species code 'MAN' for manta rays and 'RMJ', 'RMK', 'RMO', 'RME' and 'RMT' for devil rays) in red.

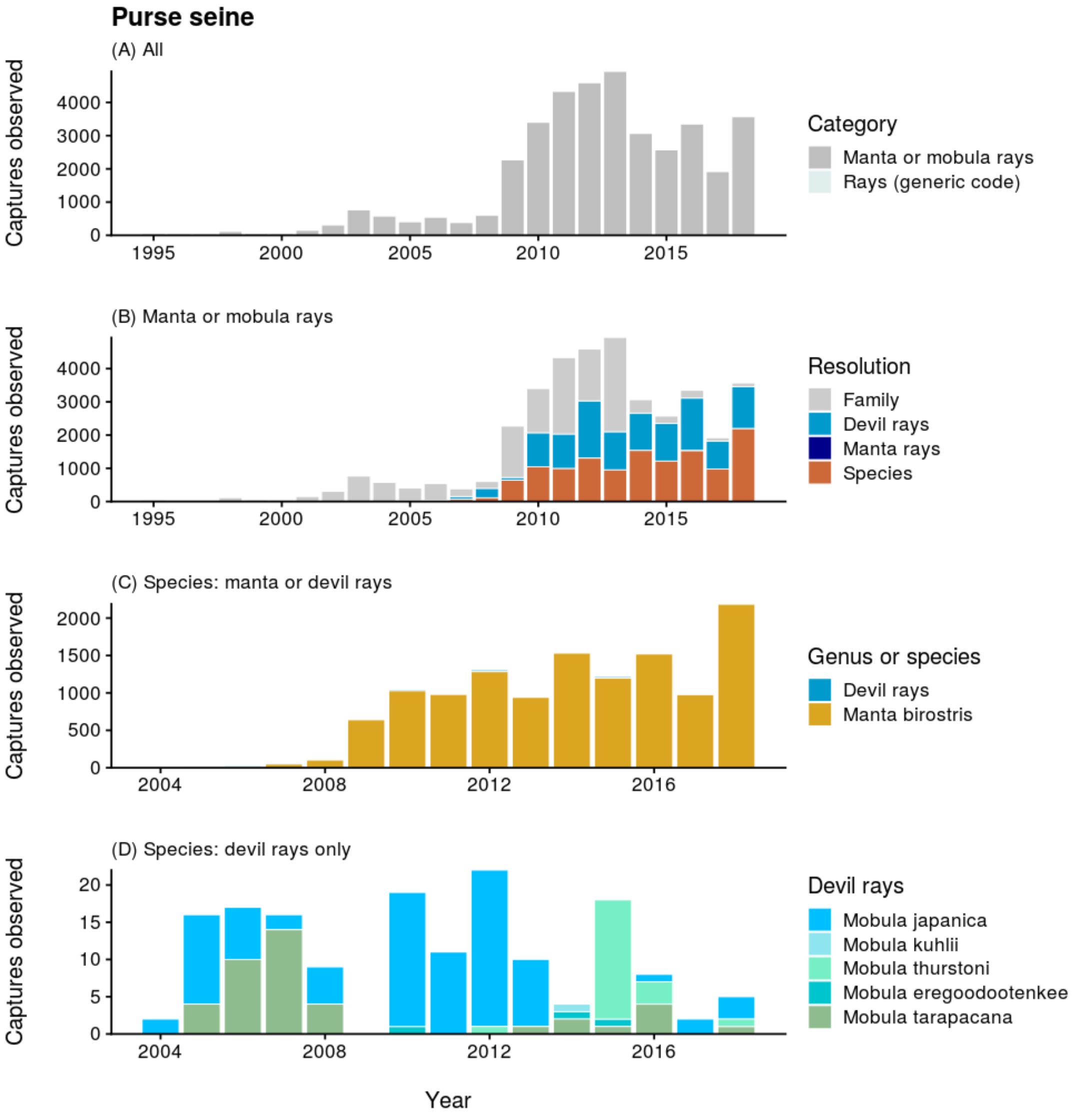

Figure 4: Total annual captures observed for manta and devil rays in purse-seine sets, aggregated under different thresholds of taxonomic resolution: (A) all records aggregated including the generic ray code 'SRX'; (B) all records minus the generic ray code, and highlighting if records were reported at the family, species group or species level; (C) only records recorded at the species level, with records for devil rays aggregated in a single category for clarity; (D) records for devil rays at the species level highlighting species breakdown within that category.

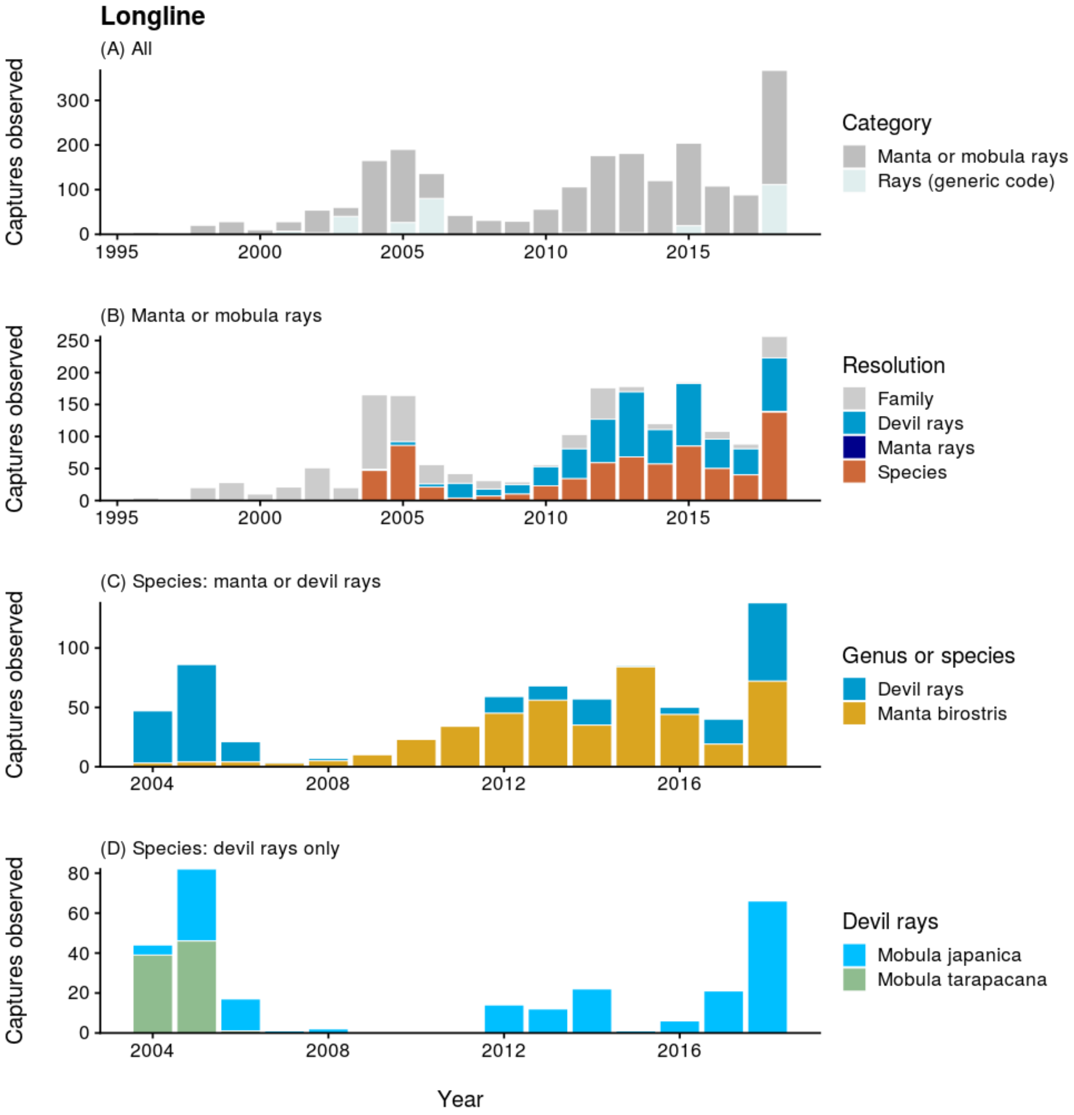

Figure 5: Total annual captures observed for manta and devil rays in longline sets, aggregated under different thresholds of taxonomic resolutions: (A) all records aggregated including the generic ray code 'SRX'; (B) all records minus the generic ray code, and highlighting if records were reported at the family, species group or species level; (C) only records recorded at the species level, with records for devil rays aggregated in a single category for clarity; (D) records for devil rays at the species level highlighting species breakdown within that category.

the capture rate was generally low, at less than four individuals per million observed hooks in most years. It was approximately 1.2 individuals per million observed hooks in the three most recent years (2016 to 2018).

Compared with manta rays, capture rates for devil rays in longline sets were higher by a factor of two (Figure 7). As for manta rays, capture rates increased from 2008 onwards, when the taxonomic resolution of the reporting increased. Subsequently, they showed an overall decrease since 2012, with an average capture rate of 2.4 individuals per million observed hooks in the last three years of the study. There was a CPUE in 2005 associated with a higher number of recorded captures of *M. mobular* and *M. tarapacana* combined with a lower observer effort.

Capture rates for devil rays identified at the species level were uninformative or highly variable for the two species with observed records, *M. mobular* (reported as *M. japanica*) and *M. tarapacana* (see Appendix A, Figure A-2). For *M. mobular*, capture rates have increased since 2015, corresponding with a parallel increase in reporting at the species level for devil rays in longline. For *M. tarapacana*, there were only three years with observations at the start of the time-series.

Catch-per-unit-effort disaggregated by set type (associated and unassociated) showed similar trends overall to the main purse seine CPUE across different taxonomic resolutions (Figure 8). There was no clear differences in CPUE between set types until 2009 when capture rates became higher in unassociated sets, for both manta and devil rays. The CPUE trend is more variable in unassociated sets but appears to increase for both manta rays and devil rays. CPUE for the combined manta and devil rays category appears to be declining since 2009 for associated sets only.

3.1.2 Spatial distribution of observed captures

The spatial distribution of observed capture rates for the combined manta and devil rays category showed a clear pattern throughout the area of purse-seine effort, with high captures in the western area (Figure 9). In this area, there appeared to be a capture "hotspot" east of Papua New Guinea in the Solomon Sea, and around Solomon Islands. This hotspot was particularly distinct in the period between 2010 and 2018, when observer effort for purse-seine sets became widespread. The same spatial pattern in observed capture rates was also apparent for both manta and devil rays when the captures were disaggregated by species group (Figure 10, and see spatial patterns of individual species in Appendix B, Figure B-3).

For longline, there was no clear spatial pattern in the distribution of CPUE for the combined manta and devil rays, although there were some localised capture hotspots in some years (Figure 11). Data were limited early in the reporting period (2000 to 2004), but overall there were higher capture rates close to the equator, with some observed captures also at higher latitudes, up to 40° N. There were few observed capture events south of 25° S, west of the dateline and north of the equator. Between 2015 and 2018, observed capture rates were relatively high in the eastern area. When distinguishing between the two species groups for manta and devil rays, observed captures of manta ray were generally high around the equator, but also in localised areas at higher latitudes (Figure 12, and see individual species in Appendix B, Figure B-4). Similarly, for the devil ray grouping, there were localised hotspots of observed capture rates in higher latitudes

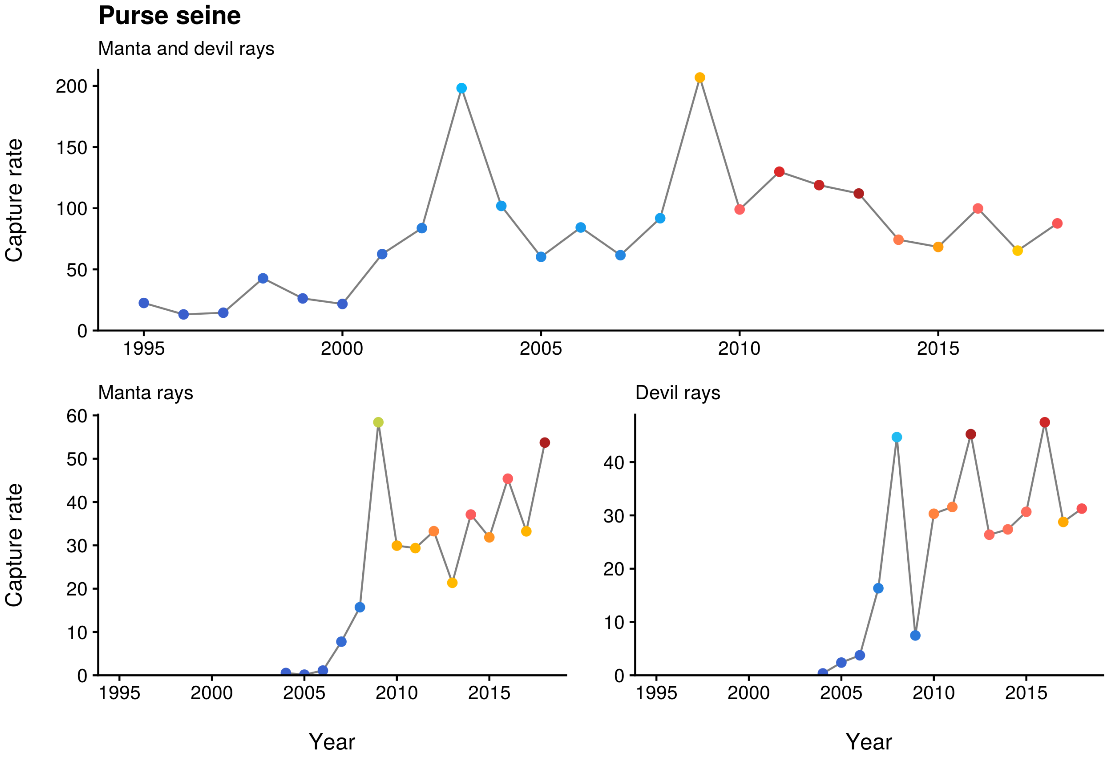

Figure 6: Catch-per-unit-effort for manta and devil rays in purse seine under different levels of taxonomic aggregation: Manta and devil rays (top), manta rays only (left) and devil rays (right). CPUE is in individual per thousand observed sets, with the point colours scaling with the observed captures (blue: low; red: high). Manta and devil ray records include both generic and specific mobulid codes with the exception of the generic ray code ('SRX'). Manta ray records included both generic ('MNT') and species-specific ('MAN') records of captures; devil ray records included both generic ('RMV') and species-specific records of captures.

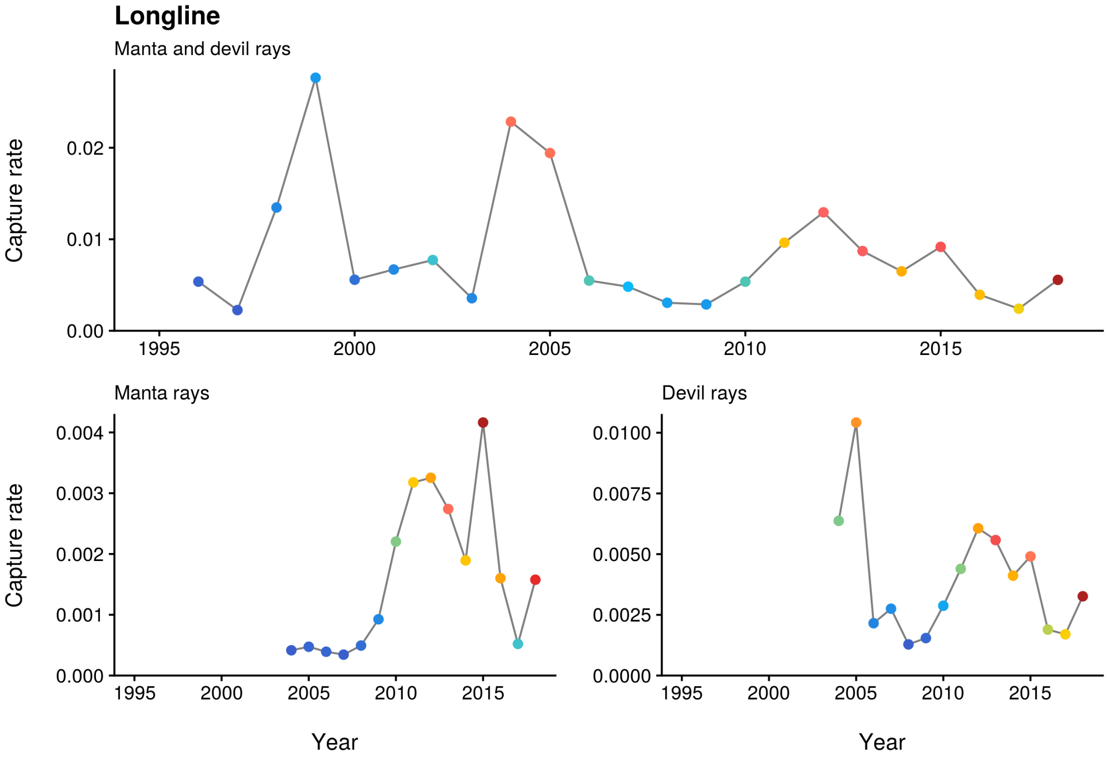

Figure 7: Catch-per-unit-effort for manta and devil rays in longline under different levels of taxonomic aggregation: Manta and devil rays (top), manta rays only (left) and devil rays (right). CPUE is in individual per thousand observed hooks, with the point colours scaling with the observed captures (blue: low; red: high). Manta and devil ray records include both generic and specific mobulid codes with the exception of the generic ray code ('SRX'). Manta ray records included both generic ('MNT') and species-specific ('MAN') records of captures; devil ray records included both generic ('RMV') and species-specific records of captures.

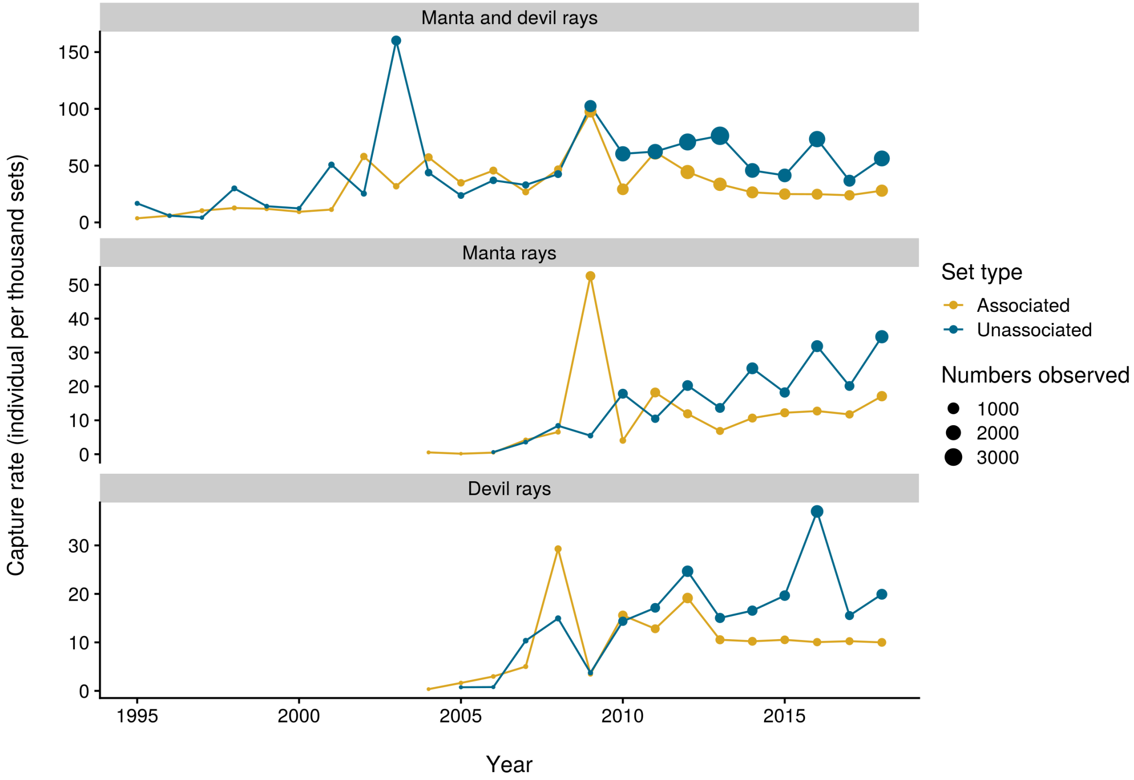

Figure 8: Catch-per-unit-effort for manta and devil rays in purse seine by set type (associated vs. unassociated), and under different levels of taxonomic aggregation: Manta and devil rays (top), manta rays only (left) and devil rays (right). Manta and devil ray records include both generic and specific mobulid codes with the exception of the generic ray code ('SRX'). Manta ray records included both generic ('MNT') and species-specific ('MAN') records of captures; devil ray records included both generic ('RMV') and species-specific records of captures. The size of the points scales with the number of observed captures.

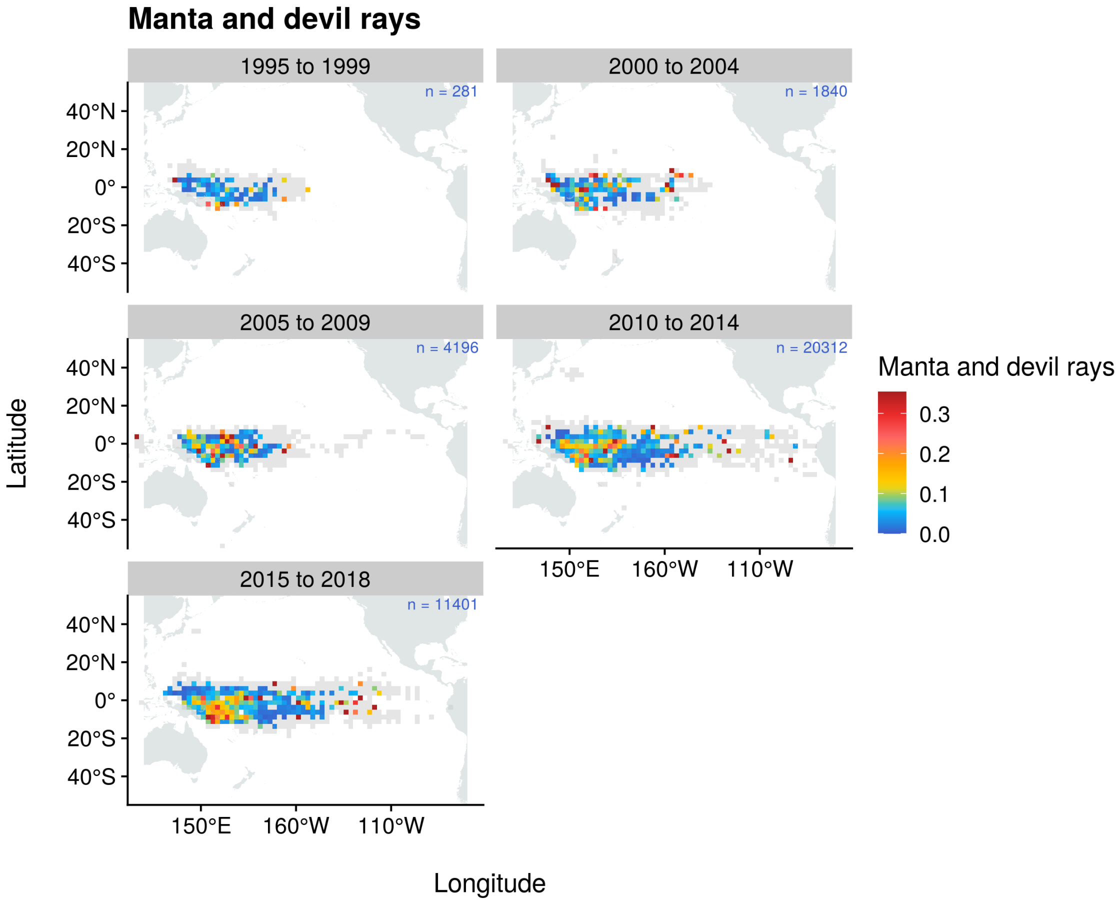

Figure 9: Spatial distribution of catch-per-unit-effort (CPUE) for manta and devil rays by time period in observed purse-seine sets, with CPUE in individuals per thousand sets scaling from low in blue to high in red. Records were aggregated into 2.5° cells. All manta and devil ray records were included, excluding the generic ray code 'SRX'.

and in the eastern area of the study region.

3.1.3 Size data and condition at release

The current analysis of existing data also considered size information from mobulid captures. Size-composition data can provide valuable insight into life-history parameters and population structure of assessed species, in addition to providing a signal of fishing intensity when there are noticeable trends in size composition over time. Relatively few manta and devil ray individuals were measured by observers, with a slightly higher proportion of individuals measured in longline compared with purse-seine sets, especially in recent years (Figure 13). For manta rays, there was a decline over time

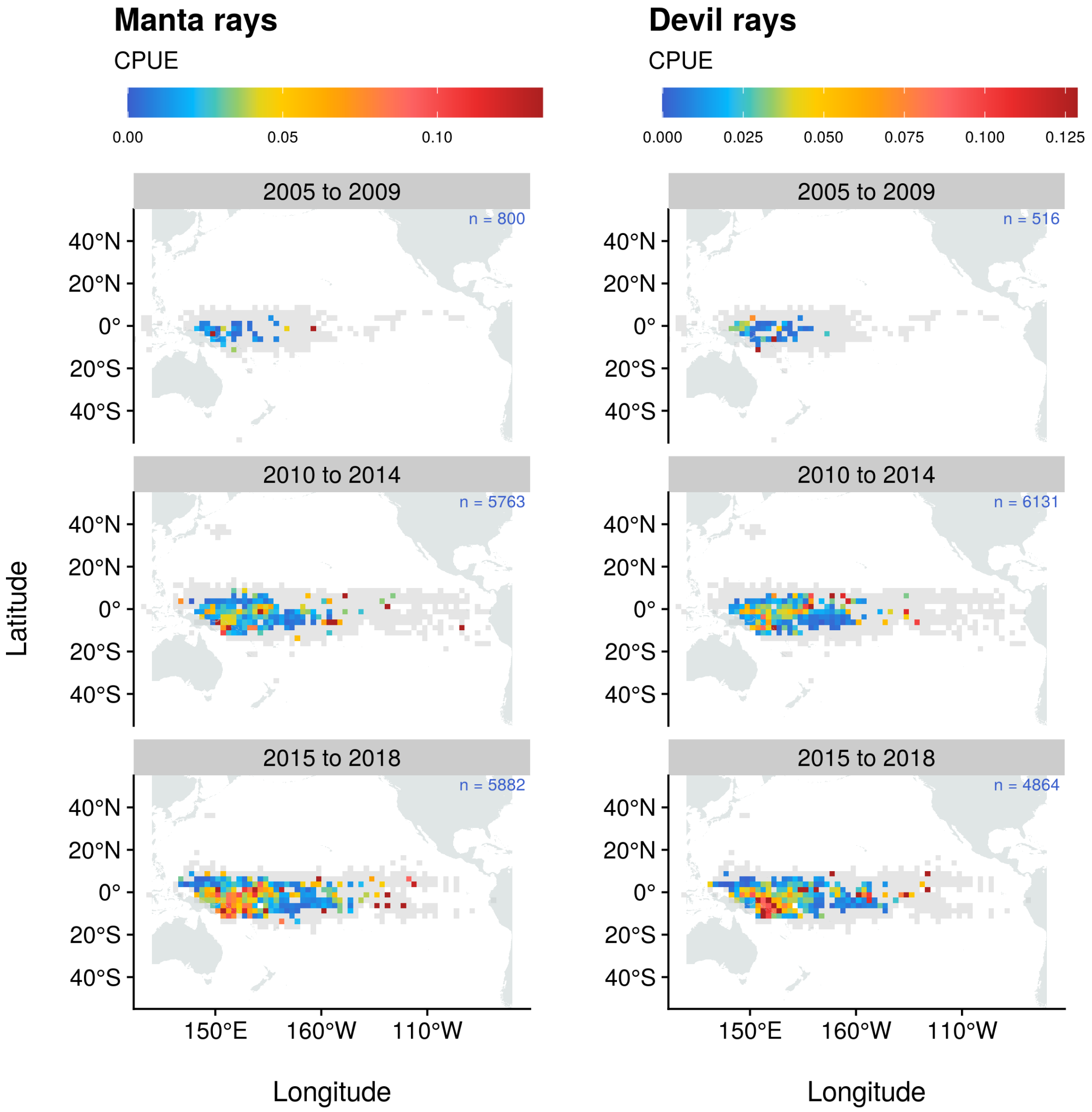

Figure 10: Spatial distribution of catch-per-unit-effort (CPUE) for manta (left) and devil rays (right) by time period in observed purse-seine sets, with CPUE in individuals per thousand sets scaling from low in blue to high in red. Records were aggregated into 2.5° cells. The number of observations is shown in the top right corner; only periods with at least 25 captures observed are shown. Manta ray records included both generic ('MNT') and species-specific ('MAN') records of captures; devil ray records included both generic ('RMV') and species-specific records of captures.

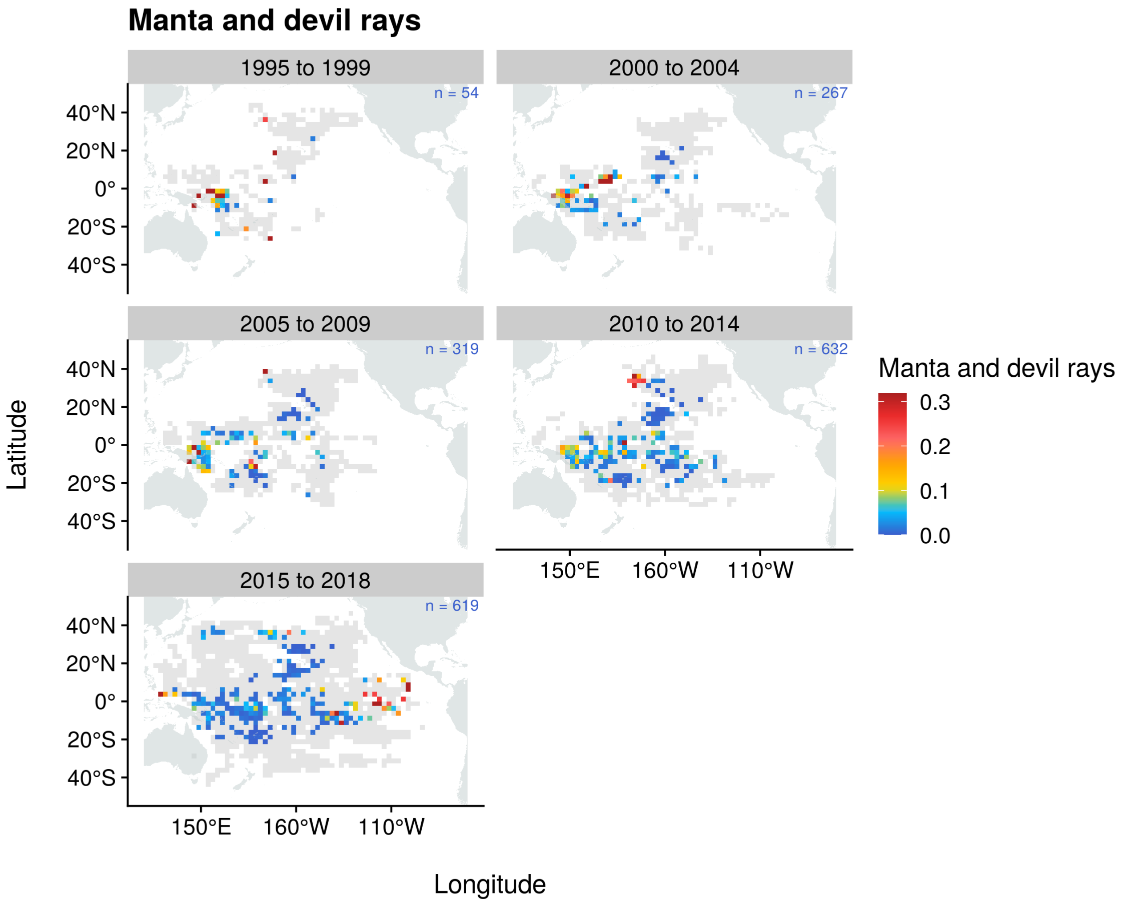

Figure 11: Spatial distribution of catch-per-unit-effort (CPUE) for manta and devil rays by time period in observed longline sets, with CPUE in individuals per thousand hooks scaling from low in blue to high in red. Records were aggregated into 2.5° cells. All manta and devil ray records were aggregated, excluding the generic ray code 'SRX'.

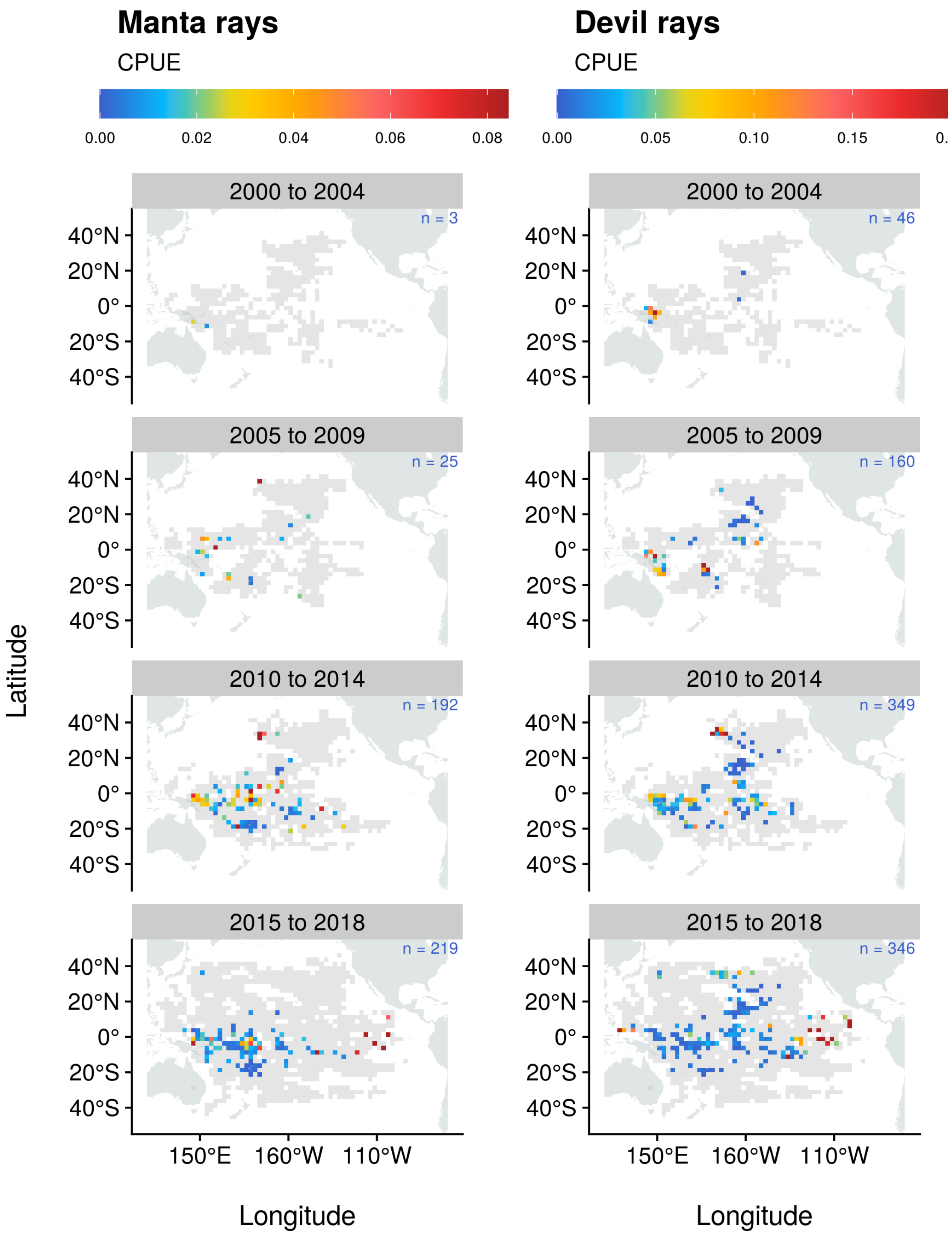

Figure 12: Spatial distribution of catch-per-unit-effort (CPUE) for manta (left) and devil rays (right) by time period in observed longline sets, with CPUE in individuals per thousand hooks scaling from low in blue to high in red. Records were aggregated into 2.5° cells. The number of observations is shown in the top right corner; only periods with at least 25 captures observed are shown. Manta ray records included both generic ('MNT') and species-specific ('MAN') records of captures; devil ray records included both generic ('RMV') and species-specific records of captures.

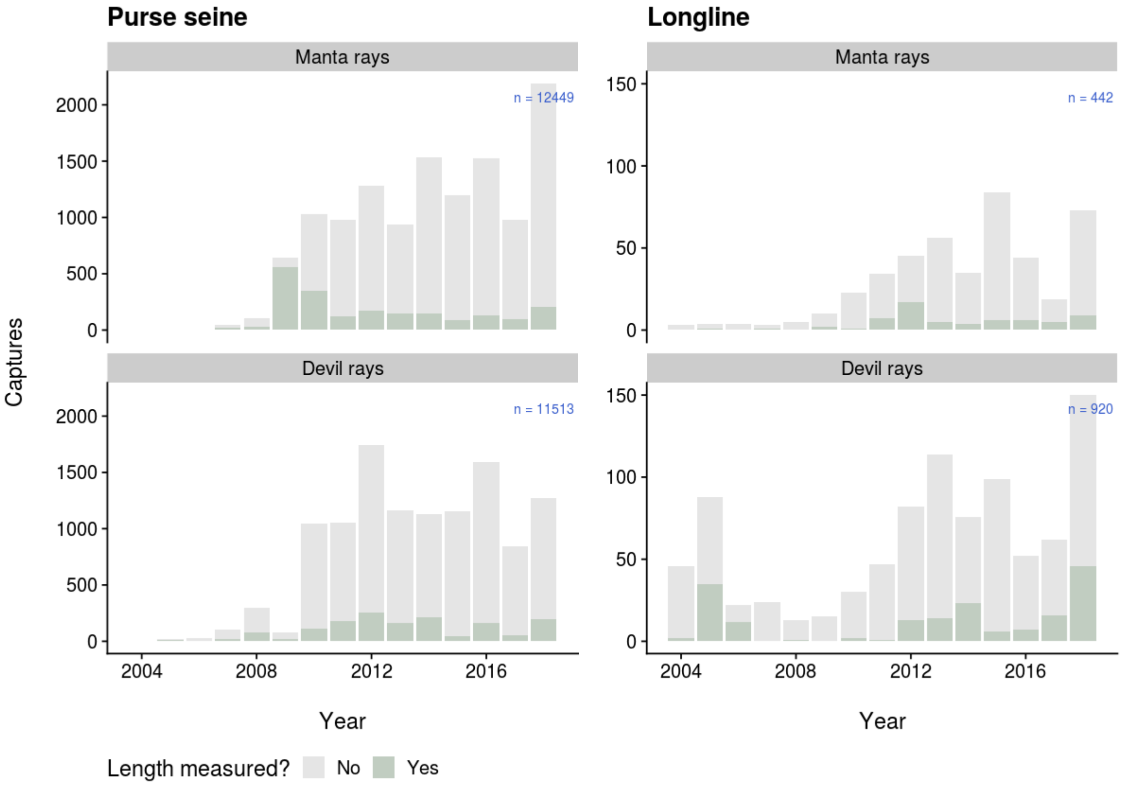

Figure 13: Number of individuals measured (green) by observer over time in purse-seine (left) and longline (right) sets, for manta (top) and devil (bottom) rays, with total annual captures shown in grey. The total number of records by category is shown in the top right corner. Manta ray records included both generic ('MNT') and species-specific ('MAN') records of captures; devil ray records included both generic ('RMV') and species-specific records of captures.

in the proportion of captured individuals that were measured; in contrast, for devil rays, the proportion of individuals measured by longline observers increased over time. For example, longline observers measured 12.3% of manta ray captures, compared with 30.7% of devil ray captures.

Of the individuals that were measured a number of records were assigned to generic codes (e.g. 'MAN' for manta and devil rays, 'RMV' for devil rays) which precludes the use of the length data given the variability in lengths within species in these groups. This impacted about two-thirds of length records for both purse seine and longline. Purse seine observers consistently use total width (wing tip to tip) (Aurélien Panizza, *pers. comm.*), while longline observers used diverse codes, but mainly 'TW' and 'TL' (total length). The two species for which length records were collected and assigned a species-level code are *M. birostris* and *M. mobular*. The highest number of length records for manta rays is in purse seine sets, and their distribution over time has mostly stayed constant with a slight decline in median length since 2009 (Figure 14, left). The overall median was 174cm. Measurements in longline sets are opportunistic and show no clear trends. For spinetail devil ray (*M. mobular*) there were slightly more length measurements by longline observers especially in recent years, although for both gears measurements are generally sparse (Figure 14, right).

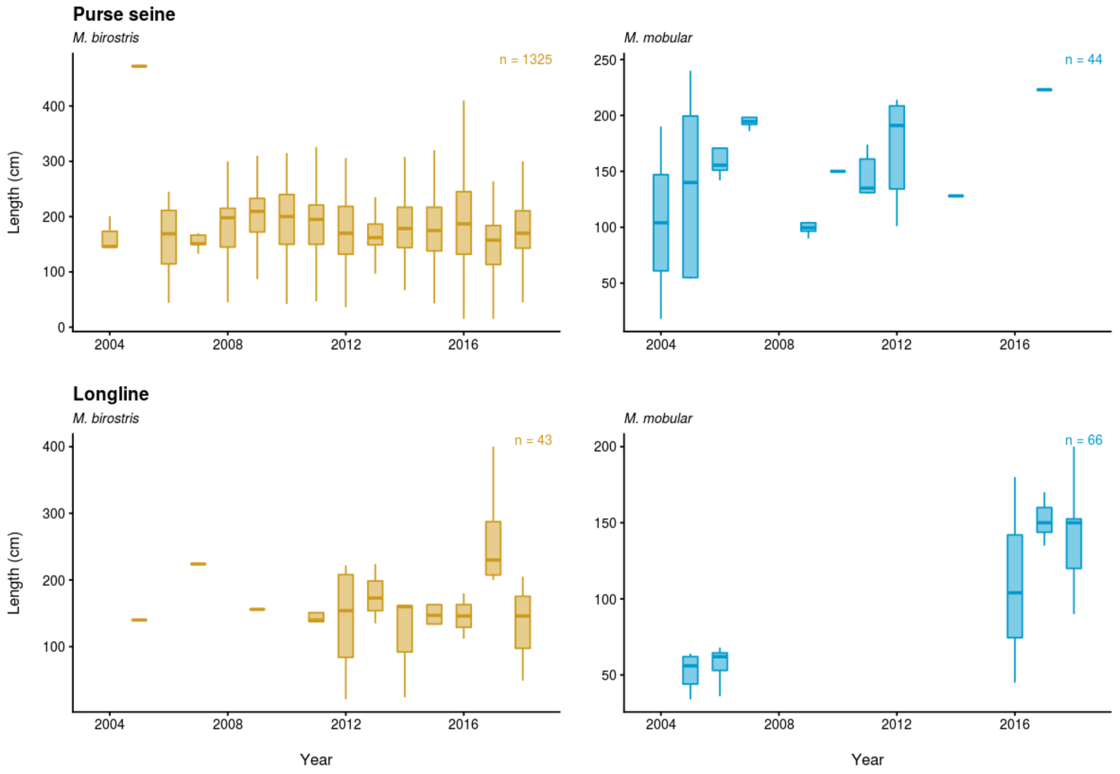

Figure 14: Distribution of observer-measured lengths (total width in cm) by species for purse seine (top) and longline (bottom) sets. Only species for which more than 20 individuals were measured and assigned to a species-level code are included. The total number of records by category is shown in the top right corner.

Observers also record the fate of captures and, more specifically, whether the individual was retained or discarded, and also the reason for discarding, when relevant. Most manta and devil rays captured in purse-seine sets were discarded under the 'Discarded, unwanted species' code ('DUS') (Figure 15). This trend was also evident when records were divided between manta and devil rays; however, a higher proportion of devil rays was retained in the earlier part of the time-series. The code 'Discarded, protected species' increased in prevalence in the two most recent years (2017 and 2018).

In longline, most manta and devil rays captures were also discarded, often under the code 'DCF', indicating that the individual was cut-off before being landed, or 'DSO', indicating that the individual struck-off before being landed. Instructions in observer form LL-4 include an example of a note that describes the length of the trace line when an individual is cut free, but an examination of the 'Notes' field for the longline dataset showed that this number is rarely noted.

The condition-at-capture is also recorded by observers and, when possible, an assessment of health for live individuals is provided under three categories 'healthy', 'injured, distressed' or 'dying' (with the corresponding codes A1, A2 and A3, respectively). This variable was seldom recorded by observers on purse-seine vessels, independently of the species aggregation used (Figure 16). There was a slight increase in 2018 of the individuals for which the condition was recorded. For these captures with information about the condition at release, about half were classified as dying or dead.

In contrast to purse seine, the condition was noted by longline observers for almost all individuals. Most individuals were classified as healthy; in recent years, a higher proportion of devil than manta rays had the condition at release recorded (i.e., code A1, A2 or A3). For example, in 2017, about 21% of manta ray individuals were classified as alive (with the condition unknown) or had an unknown status, in comparison with about 56.5% devil rays individuals.

Observers have access to a 'Comments' field in both longline and purse seine observer forms. About 11.3% of catch records had an associated comment for longline observations. These often repeated the information provided in the fate or condition fields. There were some mentions (∼15) of manta rays being tangled in the branchlines or the mainline. There was little information provided about handling. The comments field was most frequently used by purse-seine observers (∼ 52.3% of records). Like for longline, these often repeated the information provided in the fate and condition code. About 60 comments contained information about handling. Most of these noted mishandling of individuals by the crew, or that the individual was landed alive but subsequently died because of poor handling.

3.2 Life-history parameters of mobulid rays

Reviews of mobulid population information and species-specific studies highlight the general scarcity of detailed biological and life-history data for this group (e.g., Dulvy et al. 2008, Couturier et al. 2012, Broadhurst et al. 2019). Similar to oceanic pelagic shark species, the extensive distribution and large-scale movement of mobulids make population assessments and ecological studies difficult, and there are currently no global abundance data available for any of the mobulid species. In addition, the lack of historical population estimates means that there is no baseline information to determine population

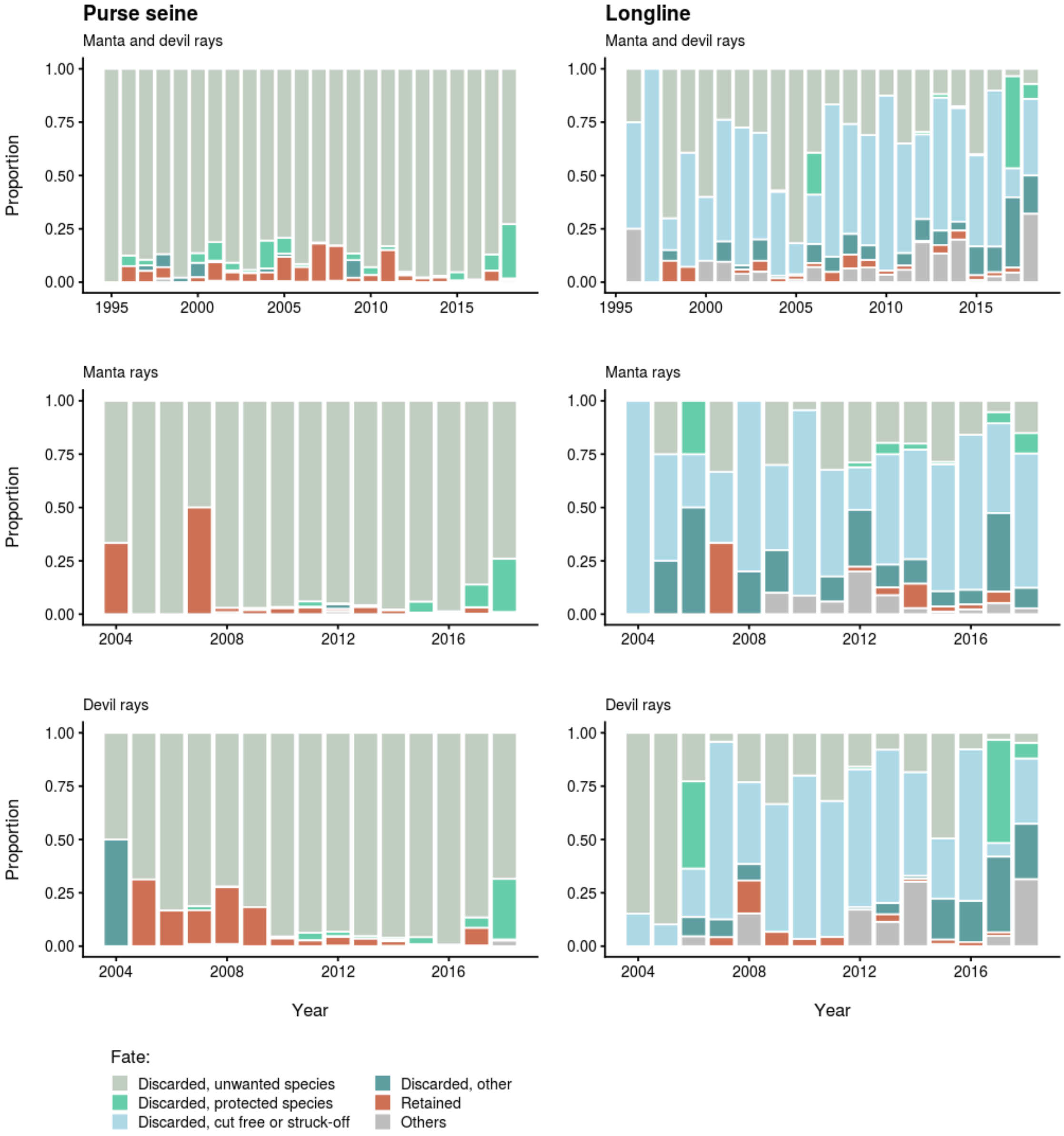

Figure 15: Distribution of of condition of release recorded by observers for captured manta and devil rays in purse seine (left) and in longline (right). Data are shown at different taxonomic aggregations: all manta and devil rays i (top), manta rays only (centre) and devil rays only (bottom).

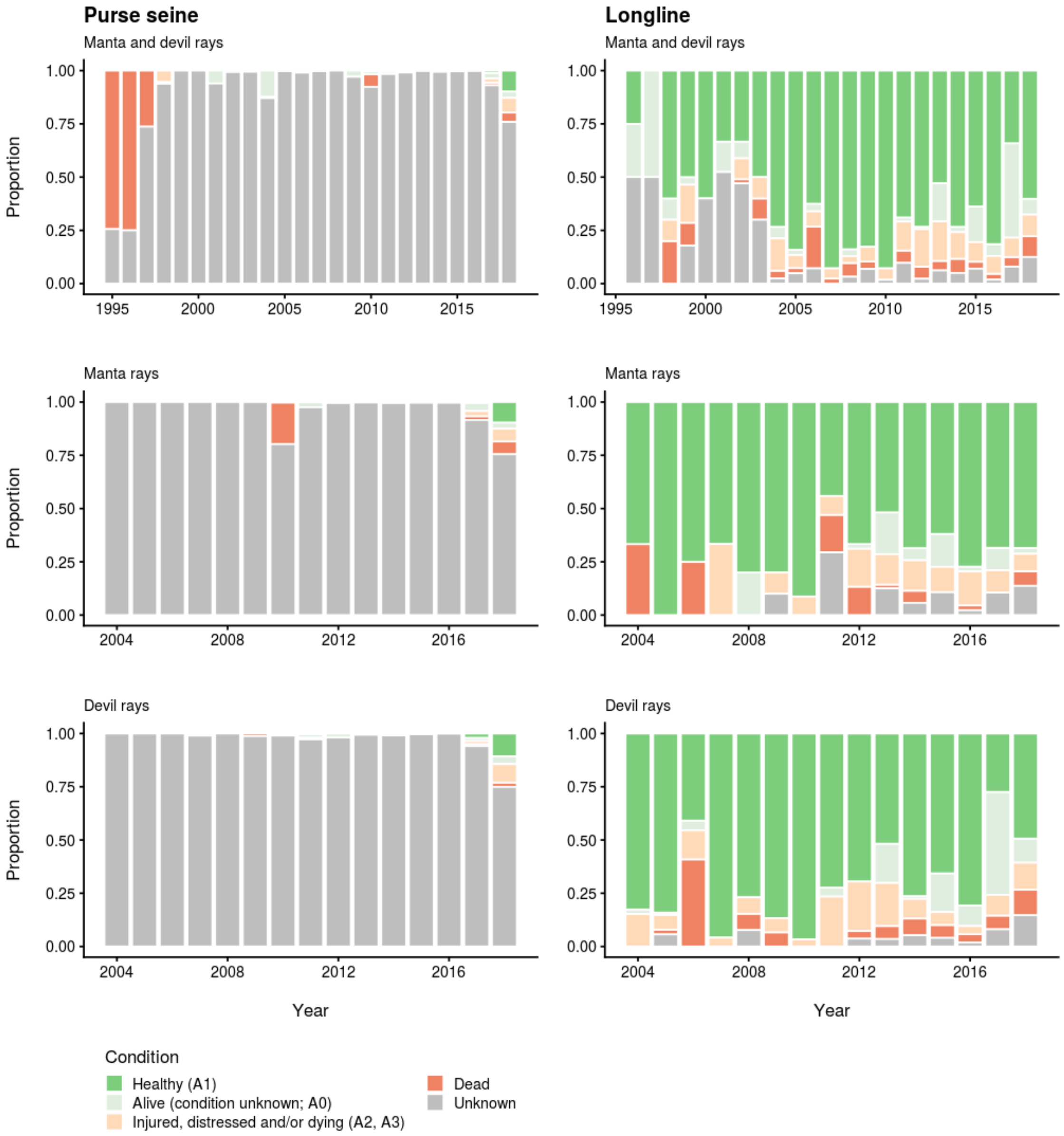

Figure 16: Distribution of individual condition at capture from observer records for manta and devil rays captures in purse seine (left) and in longline (right), under different taxonomic aggregations: all manta and devil rays individuals (top), manta rays only (center) and devil rays only (bottom).

trends. Similarly, knowledge of the population structure and reproductive biology of manta and devil rays is limited (Dulvy et al. 2014).

Population and biological data that do exist are usually from studies and monitoring programmes of different regional or local sub-populations (e.g., Clark 2010, Marshall et al. 2011, Broadhurst et al. 2019). These studies indicate some variation in life-history traits across species and regions, but highlight that this group of elasmobranchs is characterised by conservative life-history parameters, including delayed reproduction and low annual fecundity (Croll et al. 2016). Owing to these characteristics, manta and devil rays are considered the most vulnerable group of pelagic elasmobranchs. Their vulnerability is reflected in the IUCN species assessments – both manta ray species in the present study are classified as "Vulnerable", and all five devil ray species are classified as "Endangered" (see Table 1).

In view of limited knowledge of mobulid rays and substantial impacts of fishing-related mortalities on their populations, a number of recent studies have focused on population parameters that are indicative of population growth and productivity (e.g., Dulvy et al. 2014, Pardo et al. 2016, Rambahiniarison et al. 2018). These studies include different approaches to determine a maximum intrinsic rate of population growth (r_{max}), which can then be used to assess the risk of fishing impacts on mobulid populations. For example, population growth was estimated using limited life-history parameters (von Bertalanffy growth rate, pup production and age at maturity) for generic manta ray, with the estimated r_{max} value also including uncertainty (Dulvy et al. 2014). Similarly, for devil rays, r_{max} was estimated using length-at-age data, maximum size and size-at-birth of spinetail devil ray (Pardo et al. 2016); the length-at-age data used in this latter study represents the only existing data set of this kind for any species of devil ray, even though the age data remain unvalidated (Cuevas-Zimbrón et al. 2013). More recently, intrinsic population growth of *M. birostris*, *M. mobular*[japanica], *M. tarpacana* and *M. thurstoni* in the Philippines was estimated with different input parameters, i.e., size-at-pregnancy versus size-at-maturity, using an approach based on these preceding studies (Rambahiniarison et al. 2018).

Life-history data extracted from reviews and studies of mobulid species that occur in the Western and Central Pacific Ocean indicate the general lack of biological information, especially for devil rays (Table 3). For most species, there is little information of their longevity, age at maturity, natural mortality and population growth, even though recent studies have tried to address some of these shortfalls.

3.2.1 Species-specific data

Giant manta ray

Giant manta ray is an oceanic species with a circumglobal distribution that occurs at relatively low abundances (<1000 individuals at seasonal aggregation sites) throughout its range (Lawson et al. 2017, Marshall et al. 2019c). Although this species undergoes seasonal migration (exceeding distances of 1,100 km), large-scale movements are considered rare, and interchange between regional subpopulations is unlikely. In several regions, the Philippines and the west coast of Mexico, gianta manta ray populations are considered to be in decline, indicated by reported decreases in CPUE and sightings over time. The global decline of this species is considered to be over 30%.

Although abundance data are lacking, different studies of giant manta ray provide data for several biological parameters (Table 3). The maximum age of this species is unknown, but exceeds 28 years (see Stewart et al. 2018). Depending on the region, the documented size-at-maturity for females varies between 402 and 448 cm DW, with corresponding male sizes at 319 to 400 cm DW (White et al. 2006, Marshall et al. 2009, Rambahiniarison et al. 2018). The estimated age-at-maturity for female giant manta ray is eight to ten years (Marshall et al. 2018b), and the recorded mean size-at-pregnancy for this species (in the Philippines) is 532.9 cm DW (Rambahiniarison et al. 2018).

The natural mortality rate for generic manta ray has been estimated to vary between 0.012 and 0.040 per year, with a corresponding maximum intrinsic population growth rate of 0.116 (95% percentile: 0.089–0.139) per year (Dulvy et al. 2014). Another study derived estimates of r_{max} based on age-at-maturity or age-at-pregnancy (8.6 and 12.6 years, respectively) derived from size measurements, leading to r_{max} estimates of 0.019 (0.009–0.027) and 0.0001 (95% percentile: 0–0.008) per year, respectively (Rambahiniarison et al. 2018). Based on these estimates, it would take 36.5 to 86.6 years for a giant manta ray population to double in size.

Reef manta ray

Reef manta ray has a more restricted distribution than giant manta ray, and is typically found in nearshore productive areas (Lawson et al. 2017, Marshall et al. 2019c). The global population size of this species is unknown, but estimates for some of its local and regional populations generally indicate small population sizes; for example, a monitoring study of a local population at aggregation sites in southern Mozambique estimated the size of the superpopulation at 802 individuals, based on re-sightings of 449 individuals over the four-year study period (Marshall et al. 2011). Aggregation sites are widely separated, and there is low connectivity between subpopulations, with high site fidelity reported from several regions (Clark 2010, Marshall et al. 2011).

Life-history traits of reef manta ray are available from a number of studies (Table 3). Although its maximum age is unknown, reef manta ray reaches at least 31 years of age (Couturier et al. 2014). Size- and age-at-maturity for females and males varies by region, with female size-at-maturity ranging from 320 to 390 cm DW and for males from 270 to 300 cm DW (Deakos 2010, Marshall & Bennett 2010, Stevens 2016). Age-at-maturity varies for females between eight and 17 years, and for males between three and 13 years (Marshall et al. 2011, Kashiwagi 2014, Stevens 2016); it was five years for a male reef manta ray in captivity (Nozu et al. 2017). Natural mortality rates in the western Pacific Ocean (in Japan) were 0.37 (95% ci: 0.22–0.54) for juveniles and 0.06 (95% confidence interval (ci): 0.05–0.07) for adults (Kashiwagi 2014), compared with very low (close to 0) natural mortality for adults off eastern Australia (Couturier et al. 2014). Based on methods used by Dulvy et al. (2014), the maximum intrinsic rate of population growth has been estimated to range between 0.019 and 0.046 (median: 0.032) per year (Marshall et al. 2019c).

Spinetail devil ray

Spinetail devil ray is another circumglobal mobulid species, which occurs in the pelagic zone of coastal areas and on the continental shelf (Lawson et al. 2017, Marshall et al. 2018a). There are no current or historical abundance estimates for its global population, but spinetail devil ray is considered to be in decline throughout most of its range, based on identified declines in some regions (e.g., Indonesia).

Spinetail devil ray has been the subject of several biological studies, focused on determining its life-history parameters (Table 3). It is the only mobulid species to date that has been the subject of an ageing study, with findings indicating a longevity of at least 14 years (Cuevas-Zimbrón et al. 2013). Data from the ageing study were also used to estimate female age-at-maturity of this species, which was five to six years (Pardo et al. 2016). Size-at-maturity for females ranges between 207 and 240 cm DW, compared with 201 to 217 cm DW for males (Notarbartolo di Sciara 1987, White et al. 2006, Rambahiniarison et al. 2018).

The natural mortality of spinetail devil ray has been estimated at 0.087 (95th percentile: 0079–0.097) per year, with a maximum intrinsic rate of population growth of 0.077 (95th percentile: 0.042–0.108) per year (Pardo et al. 2016). Other estimates of population growth of spinetail devil ray distinguish r_{max} values that were derived from age-at-maturity or from age-at-pregnancy estimates; based on age-at-maturity, r_{max} estimates varied between 0.016 (0.006–0.024) and 0.027 (0.017–0.035) per year, compared with estimates derived from age-at-pregnancy, which ranged from 0.012 (0.002–0.020) to 0.021 (0.011–0.029) per year (Rambahiniarison et al. 2018). These estimates reflect a population doubling time of 25.7 to 43.3 and between 33.0 and 57.8 years, respectively.

Longhorned pygmy devil ray

Longhorned pygmy devil ray is relatively common in some areas throughout its distribution in the Indo-west Pacific and northern Indian Ocean (Lawson et al. 2017, Rigby et al. 2020a). There are currently no abundance data for the global population of this species, which occurs predominantly in the epipelagic zone.

Most of the biology and ecology of longhorned pymy devil ray remain unknown (Table 3); however, recent studies of individuals caught in bather-protection nets off eastern Australia provide some life-history parameters for this region (Broadhurst et al. 2018, Broadhurst et al. 2019). The latter information includes the maximum size of 130 cm DW for females and 123 cm DW for males, and size-at-maturity of 92.5 cm DW for females and 99.0 cm DW for males (Broadhurst et al. 2018). In addition, the capture records extended the southern limit of this species' distribution to 29° S.

Shortfin devil ray

Shortfin devil ray is relatively uncommon, with a predominantly inshore distribution in the Indian Ocean and western central Pacific Ocean (Lawson et al. 2017, Rigby et al. 2020b). This species occurs mainly in coastal waters and in the pelagic zone of continental shelf waters. There is comparatively little known about shortfin devil ray, and its taxonomic status (i.e., distinction from *M. eregoodoo*) was only confirmed recently (Notarbartolo di Sciara et al. 2020).

Life-history parameters of shortfin devil ray are limited to maximum size and size-at-maturity (Table 3). The maximum size recorded for this species is 122 cm DW for females and 110 to 120 cm DW for males (White et al. 2006, Notarbartolo di Sciara et al. 2017). The documented size-at-maturity is 117 cm DW for females (recorded as a pregnant female) and 102 to 119 cm DW for males (White et al. 2006, Notarbartolo di Sciara et al. 2017). There are no data for age-at-maturity, longevity, natural mortality or population growth.

Sicklefin devil ray

Another mobulid species with a circumglobal distribution is sicklefin devil ray, which occurs in tropical, subtropical and temperate waters of the Pacific, Atlantic and Indian oceans (Lawson et al. 2017, Marshall et al. 2019a). Although this species is mostly oceanic, it also occurs in coastal waters. Population data for sicklefin devil ray are limited, but indicate substantial reductions at known aggregation sites, with local and regional declines of 50–99% over the last three generations (38 years) considered likely, and similar declines currently considered to be continuing.

Biological information of sicklefin devil ray is also scarce, with the only available data of maximum size and size-at-maturity (Table 3). The maximum size documented for this species is 328 cm DW (White et al. 2006), and size-at-maturity of females varies between 218 and >236 cm DW, and for males between 202 and 252 cm DW, depending on the region (Notarbartolo di Sciara 1987, White et al. 2006, Rambahiniarison et al. 2018). Although it was included in a recent study that estimated the population growth of different mobulid species, sampling data were too limited to derive estimates for intrinsic maximum population growth for this species (Rambahiniarison et al. 2018).

Bentfin devil ray

Bentfin devil ray also has a circumglobal distribution, and occurs in shallow neritic and pelagic waters, with a seasonal appearance in productive coastal areas that are characterised by regular upwelling (Lawson et al. 2017, Marshall et al. 2019b). There are few population parameters available for this species, with general abundance data lacking.

Life-history information is limited to few parameters, pertaining to its maximum size and size-at-maturity (Table 3). Sizes vary between 168 and 180 cm DW for the largest individuals, with female size-at-maturity of 163 cm DW, compared with 150 to 158 cm DW for males (Notarbartolo di Sciara 1988, White et al. 2006, Rambahiniarison et al. 2018). Bentfin devil ray was one of mobulid species included in the recent estimation of intrinsic maximum population growth, r_{max}, using either estimates of the age-at-maturity or the age-at-pregnancy (Rambahiniarison et al. 2018). Depending on the parameters used to inform the latter age estimation, the estimated r_{max} values were 0.037 (0.027–0.045) or 0.055 (0.045–0.063) based on age-at-maturity, and 0.028 (0.018–0.036) or 0.044 (0.034–0.052) based on age-at-pregnancy. The corresponding population doubling times varied from 12.6 to 18.7 years or 15.8 to 24.8 years, respectively.

Table 3: Population information of mobulid rays (manta and devil rays) occurring in the Western and Central Pacific Ocean. Sizes are disc width (cm).

Species	Max. size (cm)	Max. age (years)	Size at maturity (cm)	Age at maturity (years)	Natural mortality rate	Max. population growth $r_{\max}$
Giant manta ray *Mobula birostris*	710	>28, up to 40 (see Stewart et al. 2018, (Marshall et al. 2018b)).	Females: 413–448, males 319–400 (White et al. 2006, Marshall et al. 2009, Rambahiniarison et al. 2018).	8–10 (12.6 at pregnancy) (Marshall et al. 2018b, Rambahiniarison et al. 2018).	0.012–0.04 per year (generic manta) (Dulvy et al. 2014).	0.116 per year (generic manta) (Dulvy et al. 2014); 0.0001 (0–0.008) per year (via age-at-maturity), 0.019 (0.009–0.027) per year (via age-at-pregnancy) (Rambahiniarison et al. 2018).
Reef manta ray *Mobula alfredi*	303–550 (Marshall et al. 2019c)	>30 (Couturier et al. 2014)	Females: 320–390, males: 270–300 (Deakos 2010, Marshall & Bennett 2010, Stevens 2016).	Females: 8–17, males: 3–13 (Marshall et al. 2011, Kashiwagi 2014, Stevens 2016).	Juveniles: 0.37 (95% c.i.: 0.22–0.54), adults: 0.06 (95% c.i.: 0.05–0.07) (Japan; Kashiwagi 2014); adults: near 0 (Australia; Couturier et al. 2014).	0.032 (0.019–0.046) per year (Marshall et al. 2019c).
Spinetail devil ray *Mobula mobular*	520 (Notarbartolo di Sciara 1987).	14 (Cuevas-Zimbrón et al. 2013).	Females: 207–240, males 201–210 (Notarbartolo di Sciara 1987, White et al. 2006, Rambahiniarison et al. 2018).	Females: 5–6 (Pardo et al. 2016).	0.087 (95th percentile: 0.079–0.097) per year (Pardo et al. 2016).	0.077 (95th percentile: 0.042–0.108) per year (Pardo et al. 2016); 0.016 (0.006–0.024) to 0.027 (0.017–0.035) per year (via age-at-maturity), 0.012 (0.002–0.020) to 0.021 (0.011–0.029) per year (via age-at-pregnancy) (Rambahiniarison et al. 2018).
Longhorned pygmy devil ray *Mobula eregoodoo*	123–130 (Broadhurst et al. 2018).	Unknown	Females: 92.5, males: 99.0 (Broadhurst et al. 2018).	Unknown	Unknown	Unknown
Shortfin devil ray *Mobula kuhlii*	122 (Notarbartolo di Sciara et al. 2017).	Unknown	Females: 117, males: 102–119 (White et al. 2006, Notarbartolo di Sciara et al. 2017).	Unknown	Unknown	Unknown
Sicklefin devil ray *Mobula tarapacana*	304–340 (White et al. 2006)	Unknown	Females: >236–280, males: 201–252	Unknown	Unknown	Unknown
Bentfin devil ray *Mobula thurstoni*	168–180 (Notarbartolo di Sciara 1988, White et al. 2006).	Unknown	Females: 163, males: 150–158 (Notarbartolo di Sciara 1988, White et al. 2006, Rambahiniarison et al. 2018).	Unknown	Unknown	0.037 (0.027–0.045) or 0.055 (0.045–0.063 per year (via age-at-maturity), 0.028 (0.018–0.036) to 0.044 (0.034–0.052) per year (via age-at-pregnancy) (Rambahiniarison et al. 2018).

3.3 Potential assessment methods

Different types of assessment can be applied to species based on the availability of fisheries data, indices of abundance and knowledge about key parameters of the species' life history, such as its distribution, growth and reproduction (Table 4).

The most comprehensive type of assessment, data-integrated stock assessments, have been used for tuna, billfish and some species of sharks in the WCPFC convention area. These assessments require time-series of catch, effort data and size composition, at least one index of abundance, growth information (e.g. size-at-age *via* a growth curve), a maturity schedule, as well as some information about movement (e.g., from tagging data) if the assessment area is divided into sub-regions.

This information is lacking or sparse for all seven of the mobulid species occurring in the WCPFC convention area, preventing the application of a data-rich assessment in the short- to medium-term. More specifically, the lack of a time-series of catch data prevents the use of both data-rich and medium data assessment types for most mobulid species, except for manta rays for which a medium data assessment (e.g., dynamic surplus production model, DSPM, Froese et al. 2017) might be achievable, due to the high taxonomic resolution in the reporting of captures and the wider availability of life-history data.

Ecological risk assessment approaches can be used in the meantime to estimate the risk of fishing impacts on mobulids in the Western and Central Pacific Ocean. There are a diversity of assessment approaches within the risk assessment category, requiring different inputs and producing different risk metrics (Table 4). Estimates of catches, recent or historical, are a fundamental component of most of these approaches. Because there are no requirements to report mobulid catches on logsheets or in official catch statistics (Clarke et al. 2017), catch time-series (recent or historical) would have to be reconstructed from observer data.

The reliability of any reconstruction depends on accurate classification of captures at the species level. The present review of existing information highlighted that observers generally reported mobulid catches at a low taxonomic resolution (family level) until recently, and that species-level classification remains limited for devil rays, especially for captures by purse-seine gear.

For manta rays, it may be possible to reconstruct a short-term time-series (e.g., for the most recent 10 years) of purse-seine catches. This period matches the transition to quasi-full purse-seine observer coverage and, given the low taxonomic resolution of observed captures in the earlier period (i.e., before 2014), is most likely to result in a representative catch history for this species. While a medium-term (10 years) reconstructed time-series of manta ray catches would be feasible, it would remain highly uncertain. In contrast, a reconstruction of recent purse-seine catches (e.g., over the last three or four years, 2015 to 2018) would likely be reliable, as almost all individuals that were observed captured in this latter time period were classified to species-level. This species-level identification by observers in recent years was considered reliable, as manta rays have distinct features that make them distinct from devil rays. In addition, the species guide used as the main resource by observers included a dedicated page to manta ray (Chapman et al. 2006). Nevertheless, an underlying assumption of the potential catch reconstruction would be that only giant manta ray (*M. birostris*) was bycaught in purse seine and longline, even

Table 4: Overview of input data required by medium data and data - poor assessment approaches for mobulid rays. Historical catch data need to include data from a minimum of 10–15 years. Required inputs are indicated by ×; optional inputs or inputs requiring lower precision are indicated by ∼. DSPM, dynamic surplus production model; SRA, spatial risk assessment; eSafe, Sustainability Assessment for Fishing Effects; EASI - FISH, Ecological Assessment of the Sustainable Impacts by Fisheries; PSA, Productivity - Susceptibility Analysis.

Input	DSPM	Depletion-based	SRA	eSAFE	EASI-FISH	PSA
Fisheries data						
Catches (recent)			×	×	×	∼
Catches (historical)	×	×				
CPUE	×					
Size composition	×					
Life-history						
Abundance			×	∼		
Distribution			×	×	×	
Growth	×		∼	∼	∼	∼
Maximum length	×		∼	∼	∼	∼
Age (size) at maturity			∼	∼	∼	∼
Fecundity			∼	∼	∼	∼

though its distribution overlaps with that of reef manta *M. alfredi*. The reconstruction would also require assumptions about post-release mortality until this variable has been further researched (see below).

Because manta rays were predominantly captured in purse-seine gear, which has higher observer coverage than longline, the resulting catch reconstruction is also likely to be more reliable. A reconstruction of longline catches for manta rays would be more difficult, given the markedly lower rate of captures compounded by low observer coverage. Nevertheless, almost all manta ray individuals that were captured in longline gear were discarded or cut free, so that mortality from longline gear is expected to be considerably lower than mortality in purse-seine gear.

In comparison with manta rays, a catch reconstruction for devil rays would be challenging, even for the most recent years, as capture records continue to lack the required taxonomic resolution to the species level, especially in purse-seine sets. For example, capture records in 2018 indicate that out of the 1268 observations classified as devil rays by purse-seine observers, only two captures were identified at the species level. This limitation was considerably less evident in longline observations, with 66 out of 84 individuals that were classified as devil rays identified at the species level. One option to address the limitation of species-level identifications for devil rays would be to reconstruct catches at the level of the species group, and then assign catches by species based on environmental preferences of individual devil ray species. In addition, as devil rays appear more vulnerable to longline gear than manta rays, mortality from longline gear should be accounted for with higher priority for this species group.

Another important aspect for any catch reconstruction is the high proportion of bycaught individuals that were discarded, necessitating the need to account for post-release mortality. For example, between 2016 and 2018, about 98% of individuals caught in purse-seine gear and 64% of individuals in longline gear were discarded. Safe-release guidelines were discussed at the WCPFC Scientific Committee meeting in 2017 (Hutchinson et al. 2017), but the extent of their uptake by fishing crew is unclear . A brief survey of observer notes that accompany capture records contained limited information about the use of safe-release methods.

Furthermore, information about the condition of individuals that were captured is frequently missing from observer records, including in recent years (i.e., 2016 to 2018). This aspect is particularly pertinent for purse-seine sets, for which this information is lacking for 90.5% of individuals, compared with 18.8% of individuals in longline sets. For this reason, one of the top priorities for observers on purse-seine vessels is to increase the recording of the health condition of mobulid captures.

For longline gear, most individuals were classified as "healthy" when released (condition code A1), but it is unclear to which extent observers were able to accurately assess the health condition of captured mobulids. This uncertainty means that the survival of individuals classified as healthy needs to be assessed, for example, through tagging studies such as used recently in Common Oceans (ABNJ) Tuna Project 2019.

Potential assessment approaches for the short- to medium-term for mobulids include a number of options (Table 5). For manta ray, several studies have provided estimated life-history parameters, including estimates of individual growth and of the maximum intrinsic rate of population growth, r_{max} (see Table 3). Based on these parameters, a DSPM (e.g., Just Another Bayesian Biomass Assessment (JABBA) Winker et al. 2018) could be applied to this species, pending catch reconstruction and CPUE standardisation as inputs. The prior for r_{max} could be further refined based on the Euler-Lotka equation following Pardo et al. 2018 (see Neubauer et al. (2019) for an application to oceanic whitetip shark, *Carcharhinus longimanus*). A surplus production model could provide a time-series of population status compared to biological reference points such as F_{msm} and F_{crash} (Zhou et al. 2018). Ideally, a time-series of catches and unbiased CPUE spanning 10 to 15 years would be available to support such an approach. The CPUE standardisation remains the main challenge for a short-term application. There is a clear signal of reporting still present in the nominal CPUE at least until the 2010s (Section 3.1.1) and DSPM requires an unbiased CPUE to constrain the time-series of abundance. Ideally, this index should include data from at least 10 years, which means that a reliable standardised CPUE for manta rays is unlikely to be available in the short term (i.e., within the next two to three years).

A DSPM could still be applied for manta rays, but in view of multiple sources of uncertainty in this analysis, and the length of the time-series, it should be supplemented by alternative approaches. For instance, depletion-based methods rely on historical catch data (only) and can provide broad estimates of population status (e.g. Carruthers et al. 2014). It would also be possible to use a spatial risk assessment method based on the eSAFE (Sustainability Assessment for Fishing Effects) approach developed by Zhou et al. 2013 (e.g., see also Neubauer et al. 2019 for oceanic whitetip shark;), which requires assumptions about gear efficiency and the area impacted by fishing gear. Alternatively, if a population estimate becomes available, a spatially-explicit risk assessment could be applied to this species (e.g., Neubauer et al. 2018). There are currently no population estimates available for manta ray in the Western and Central Pacific Ocean, but there are some regional abundance estimates for this species (e.g., Beale et al. 2019), which might

Table 5: Overview of potential medium data and data-poor assessment approaches that could be applied to mobulids in the Western and Central Pacific Ocean. Timeframes are based on the likelihood of an informative assessment. DSPM, dynamic surplus production model; SRA, spatial risk assessment; eSafe, Sustainability Assessment for Fishing Effects; EASI-FISH, Ecological Assessment of the Sustainable Impacts by Fisheries; PSA, Productivity-Susceptibility Analysis.

Species	DSPM	Depletion-based	SRA	eSAFE	EASI-FISH	PSA
Giant manta ray *Mobula birostris*	5 years	5 years	Now	Now	Now	Now
Reef manta ray *Mobula alfredi*						Now
Spinetail devil ray *Mobula mobular*	5–10 years	5–10 years		2–3 years	2–3 years	Now
Longhorned pygmy devil ray *Mobula eregoodoo*				5 years	5 years	Now
Shortfin devil ray *Mobula kuhlii*				5 years	5 years	Now
Sicklefin devil ray *Mobula tarapacana*				5 years	5 years	Now
Bentfin devil ray *Mobula thurstoni*				5 years	5 years	Now

be used to estimate abundance at a broader scale.

The absence of catch history for devil rays precludes the use of data-rich or medium data assessments, but there are a number of data-poor assessment approaches that could be used for both manta and devil rays (Table 5). These approaches would not provide a time-series of F in relation to management or biological reference points, but they could be used to determine whether current levels of fishing pressure are likely to be unsustainable for a particular mobulid species, or help rank species in terms of conservation priorities.

A recently-developed approach that might be adapted to both manta and devil rays in the Western and Central Pacific Ocean is that of EASI-fish (Ecological Assessment of the Sustainable Impacts by Fisheries, Griffiths et al. 2019). This framework has some parallels with spatially-explicit risk assessments and eSAFE, as it uses information about the species' distribution and its overlap with fishing effort to generate an estimate of fishing mortality. It also does not require a time-series of captures. It can produce a suite of biological reference points (e.g., fishing mortality (F) and spawning stock biomass (SSB)-based reference points), which can be used to inform managers, prioritise species or be updated in successive analyses. Different options for the parameterisation of key components are provided depending on the information available for each species. In addition, the model is parameterised by length instead of age, which expands the scope of life-history studies that can be incorporated.

For devil rays, one of the likely key challenges is the lack of species identifications, which would preclude the estimation of suitable environmental parameters for these species in the Western and Central Pacific Ocean based on observations by the Regional Observer Program. One alternative might be to supplement the capture records from the Western and Central Pacific Ocean with capture data from the Inter-American Tropical Tuna Commission (IATTC) observer programme, as the latter dataset includes higher species resolutions for devil rays. This approach would assume that the fitted environmental relationships from the IATTC data are also relevant in the Western and Central Pacific Ocean.

An alternative framework for assessing the vulnerability of devil rays that are data poor is a Productivity-Susceptibility Analysis (PSA) (Stobutzki et al. 2001). This framework has been widely applied to rank vulnerability to overfishing within designated species assemblages, without the need for detailed knowledge about catch or life-history (e.g., Patrick et al. 2010). Within this framework, vulnerability is a function of productivity (the potential to recover from depletion) and susceptibility (the degree of catchability by a given type of fishing gear). These two components are estimated for each species by assigning an arbitrary rank for several attributes related to each category, and combining them into a final metric (e.g., for productivity, maximum age: low, medium or high; for susceptibility, desirability of catch: low, medium, high). Although the PSA framework does not provide the population status as a function of a reference point, outputs can be used to inform the allocation of resources for further research. For example, a PSA was recently used in the IATTC region to rank vulnerability of a range of species including teleosts and elasmobranchs (Duffy et al. 2019). In this analysis, giant manta ray was found to have the highest vulnerability to overfishing out of the 27 species tested for the Eastern Pacific Ocean. The data requirements for PSA are relatively low as species are ranked according to a set of attributes defined by the researchers. Because this approach does not require accurate or detailed catch histories, it is most relevant to devil rays. Nevertheless, the outcomes would only apply to the species assemblage included in the analysis; for example, the PSA would rank the vulnerability of *M. mobular* to overfishing compared with *M. thurstoni*, but not provide tractable measures of population status beyond the initial species ranking.

Finally, it is recommended that any of the analyses are based on the application of a Bayesian framework, so that the uncertainty in the input data and life-history parameters can be propagated in other components of the assessment, including any reference points produced as output. A Bayesian approach would also allow an explicit framework to include information on poorly-studied life-history or other key parameters *via* priors. For example, Neubauer et al. 2018 developed priors for post-release mortality for a spatial risk assessment of whale shark (*Rhincodon typus*) in the Western and Central Pacific Ocean from a Delphi survey of expert opinions.

4. DISCUSSION

This review of data holdings and assessment feasibility for mobulids in the WCPFC region found an improvement in the quality of the data available from observer records (compared with an earlier assessment in 2016; Tremblay-Boyer & Brouwer 2016), but also highlighted several gaps in key knowledge pertaining to this group of elasmobranchs.

Observed mobulids capture were much higher for purse seine than longline. This reflects in part the much higher rate of observer coverage on purse seine vessels but also the tropical distribution of many mobulid species. Manta rays, being filter feeders, should also be more vulnerable to purse seine than longline gear.

A basic but fundamental variable required for most assessment types is catch data at the species level, but this information is not consistently provided in the observer data. As some species of mobulids are difficult to distinguish, and changes and updates to the phylogeny of mobulids further challenge species identifications, it is difficult for observer to correctly assign species codes. This aspect was already highlighted in the recommendation of improved observer training for the identification of mobulids from the 16th meeting of the Scientific Committee, and it still remains an issue.

Although manta rays are now assigned a species-level code in most observer records, captures of devil rays continue to lack a species-level classification by observers, especially in purse seine. Within the devil rays grouping, recent records at the species level were almost exclusively for spinetail devil ray (*M. mobular*). Spinetail devil ray is the largest species in this group, and its identification may be easier compared with other devil rays owing to its size. The scarcity of species-level records for smaller species of devil ray indicates the lack of observer training for distinguishing features other than size.

Among the mobulid species captured, giant manta ray (*M. birostris*) had the most data to inform an assessment in the Western and Central Pacific Ocean. In an analysis of IATTC observer data, this species was recently classified as the most vulnerable to fishing in the Eastern Pacific Ocean (Duffy et al. 2019). The comparative analysis also included two species of devil ray (*M. mobular* and *M. thurstoni*), highlighting that *M. birostris* should be prioritised for an assessment within the mobulid group, based on data availability and also from a management perspective.

The current review did not produce any standardised indices of abundance, but the lack of a clear trend evident in the nominal CPUE for manta ray, together with trends in reporting, is likely to make the implementation of a population dynamics model difficult under a medium data assessment approach. A spatial risk assessment based on a recent catch history (e.g., SAFE, Zhou et al. 2013) is probably most suited for an assessment of this species. Once a more extensive, and reliable, catch history of at least 10 to 15 years is available (from reconstruction), the assessment could be upgraded to a medium data assessment. In addition, the CPUE abundance signal could be supplemented by length data, and eventually be incorporated in a data-rich assessment on the longer term. Most length measurements in the current observer data set were collected for manta ray, but there was no clear trend in median length over time. Furthermore, most observed captures had no associated length data recorded, even in recent years. While it is challenging for observers to obtain accurate length measurements from individuals that are not brought on deck (e.g., when the line is cut to release the animal), approximate length estimates can still be informative, and are being collected by some observer programmes (e.g., the United States observer programme operating in the Hawaiian archipelago and in American Samoa).

A recent difficulty in a data collection context is the taxonomic distinction of a new species of manta ray, reef manta *M. alfredi* that occurs sympatrically with giant manta ray. The current data review assumed that all manta ray captures were correctly identified as giant manta ray, based in part on its oceanic habitat preference, which would make it more vulnerable to pelagic fisheries than reef manta ray. Nevertheless, although reef manta ray is mainly found in nearshore habitats and often occupies the same site over time, individuals are known to undertake seasonal migrations (Anderson et al. 2011), which could increase their vulnerability to pelagic fisheries. Small differences between the two species of manta ray occurring in the Western and Central Pacific Ocean may make identification by observers at the species level dubious. Non-lethal tissue collection of manta rays by observers for DNA testing could help assess the validity of the assumption that giant manta ray is the main manta ray species featuring in observer records in this region.

Observers should be able to distinguish manta rays from devil rays; however, the generic ray code and the generic Myliobatidae family code continue to be used, especially by longline observers. The lack of identification at the species level, particularly for devil rays, may be due to the commonly-used species identification manual, which only includes manta rays and devil rays as a group (i.e., *Mobula* spp., with the code 'RMV') (Chapman et al. 2006). An updated version focused on shark and rays was recently published (Park et al. 2019), but has yet to be used widely. It is currently available online[1], and it is recommended that other ways to increase its accessibility are investigated, such as a smart phone app, species identification posters at key landing locations, or waterproof ID cards for a subset of key species for observers to carry on-deck. As this updated guide includes more species of manta and devil rays, including *M. alfredi*, it is likely to improve the taxonomic resolution of observer records; however, it still lacks one species of devil ray residing in the Western and Central Pacific Ocean, longhorned pygmy devil ray (*M. eregoodoo*). It is also worth noting that the designation of the *Manta* genus is retained in the manual, which may hamper the interpretation of the generic *Mobula* spp. code that has been used for devil rays, but no longer corresponds with the most recent taxonomy.

Because most mobulid captures are discarded, a key parameter for quantifying the impact of fishing on mobulid populations is post-release mortality. To incorporate this parameter in catch histories, it is necessary to have an estimated value as a function of whether the individual was released healthy or injured. It is recommended that the post-release survival of individuals classified as healthy at the time of release is investigated *via* tagging studies. An approach developed for the tagging of sharks using popup archival tags in the Western and Central Pacific Ocean could possibly be adapted for mobulids (Common Oceans (ABNJ) Tuna Project 2019, see also Francis & Jones 2016 for a study using popup archival tags on *M. mobular*). In parallel, there were some distinct differences between purse-seine and longline observer data regarding the recording of the condition at discard, a variable also required to estimate post-release mortality. In purse seine, the condition at capture was not recorded for most individuals (although there appeared to have been an improvement in the reporting in 2018, the last year of the study). In longline sets, this variable was recorded for most individuals; however, in recent years there was still a considerable proportion of individuals that were recorded as alive, but without a health classification. Also, most individuals discarded from longline sets were classified as healthy, but it would be useful to validate this classification. One option would be to access e-monitoring recordings for sets having discarded mobulids under a 'Healthy' condition, and assess the range of individual conditions that result in this classification.

The ongoing lack of consistent classification of devil rays at the species level impedes the application of any assessment approach that requires catch histories. One of the main

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[1] https://coastfish.spc.int/en/component/content/article/44-handbooks-a-manuals/507-shark-and-ray-identification-manual

data-poor assessment options that does not require a catch history is the Productivity-Sustainability Analysis (PSA); this analysis could be applied to devil rays. Although this approach would not provide metrics of population status compared to reference points, it could assist in the prioritisation of research and observer training for the smaller species of devil ray, for which identifications at the species-level have been limited. On the short-to-medium term, a quantitative risk assessment approach such as SAFE or easi-FISH could also be applied to the spinetail devil ray for which more information on captures are available at the species-level.

Safe-release guidelines for mobulids have been proposed to the Scientific Committee (Hutchinson et al. 2017, A. et al. 2019). If followed by fishing crews, these guidelines are likely to decrease post-release mortality of mobulids. There is currently no formal way for observers to record whether these guidelines are being followed, except possibly in the "notes" field of observer forms. The current review of this field in both purse-seine and longline forms found little consistent information pertaining to the application of safe-release guidelines. The few comments on that topic noted the guidelines were not followed.

While there is a range of data-poor assessment approaches that can be applied to mobulids based on the specific data availability for each species, the true status of the stock for this group will remain uncertain on the medium to long term. A management metric that could be collected and monitored for improvement is the combined implementation of safe release guidelines and the resulting condition of individuals at release. Improving these inter-related variables will have an immediate, positive impact on the survival of bycaught individuals and lower the overall fishing mortality on populations of mobulids in the WCPO. A section in the new species guide contains a dedicated section on safe-release guidelines which will hopefully broaden the reach of application of these methods (Park et al. 2019). However, implementation should still formally be monitored, e.g. by amending the observer forms to include information about the use of safe-release guidelines. This information would improve estimates of post-release mortality and also support the allocation of training resources amongst observer programmes, if there are differences in the implementation of safe-release guidelines between specific programmes. E-monitoring could also also provide an independent verification of the implementation.

In view of the vulnerability of mobulid rays and the impact of fishing on their populations, additional research regarding their population abundance and life history is also vital. Lethal sampling methods can provide valuable insights into key parameters like growth and fecundity but should be avoided by researchers given the uncertain status of the stocks. However, a high number of bycaught mobulids are brought on-deck already dead. It might be possible to expand the scope of sampling of mobulids by observers so that key samples are collected from these dead individuals, such as the vertebrae which do not require specialized storage facilities on the short-term and could provide valuable information on growth. Such expanded sampling would require initial consultation with observers and trainers within the Regional Observer Programme to assess feasibility across different tissue types. The Pacific Specimen Tissue Bank could serve as a repository for new mobulid samples and a point of coordination between biologists studying mobulids in the Pacific.

Recommendations

Based on the current review of data and feasibility study of potential assessment approaches for mobulid rays in the Western and Central Pacific Ocean, we make the following recommendations to the 16th Regular Session of the Scientific Committee:

- For manta ray, a quantitative risk assessment like a spatial risk assessment, eSAFE or easi-FISH should be developed in the short-term, given the relative availability of data amongst mobulids and the high risk of overfishing based on its life-history.
- For the six other species of mobulids, a semi-quantitative data-poor assessment like a Productivity Susceptibility Analysis should be considered in the short-term to prioritise resource allocation regarding their relative vulnerability to overfishing.
- For spinetail devil ray (*M. mobula*), the feasibility of a quantitative risk assessment should be considered in three to five years' time; within the devil ray group, this species was frequently identified at the species level, and is likely at risk of overfishing due to its life history.
- A metric capturing likely drivers of post-release mortality (e.g. application of safe-release guideline, condition-at-release) should be developed, collected and monitored while assessments of stock status remain uncertain.
- Tools to monitor the application of safe-release guidelines should be developed, e.g. based on amended observer forms or collection of sampling footage from e-monitoring.
- Observers should be given additional training for the identification of smaller devil ray species like *M. thurstoni*, *M. eregoodoo* and *M. tarapacana*. Special attention should be given to *M. eregoodoo*, as this species is not included in the most recent version of the species identification guide.
- Additional media should be explored to enhance the accessibility to resources in the new identification manual; potential options include a smart-phone application, identification cards and identification posters at key landing locations.
- Research into potential approaches for estimating post-release mortality of mobulids in the Western and Central Pacific Ocean should be investigated, such as the use of pop-up archival tags.
- Approaches to sample dead bycaught mobulid individuals should be investigated for use in biological studies, including the potential of the Pacific Specimen Tissue Bank to serve as repository, and point of coordination amongst mobulid biologists.
- The assumption that giant manta ray (compared with reef manta ray) dominates bycatch in tuna fisheries should be verified by DNA testing of tissue collected from bycaught individuals using non-lethal approaches.
- The extent of tangling as a cause for giant manta ray bycatch in longline gear should be documented; mitigation methods should be researched if the tangling is found to be widespread.

- Observers should be encouraged to photograph devil rays so that species identifications can be verified; a sampling programme of the collected photographs should be designed to ensure they are monitored regularly and are representative of trends within the the observer programme.
- E-monitoring options to improve species identification and assessment of individual condition at discard should be explored.
- Longline observer coverage should be increased to improve the reliability of catch reconstructions and increase the ability to characterise fleet-wide fishing impacts, particularly for rare mbulid species.
- Observers should be trained to estimate the length of bycaught individuals at a distance, including the development of a length code, based on the high number of individuals that are cut free before being brought on deck.

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APPENDIX A: CPUE for devil rays reported at the level of species

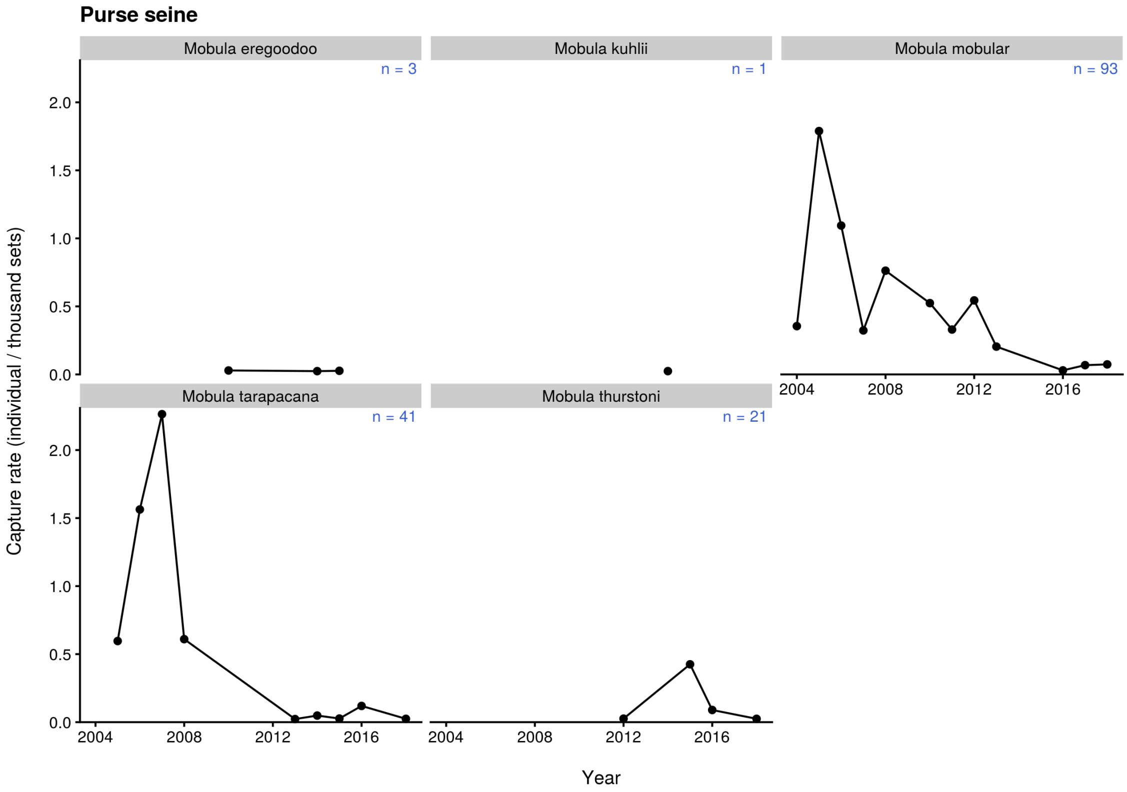

Figure A-1: Catch-per-unit-effort in individual per thousand sets for devil ray records identified at the level of species by purse-seine observers. The number of observations is shown in the top-right corner.

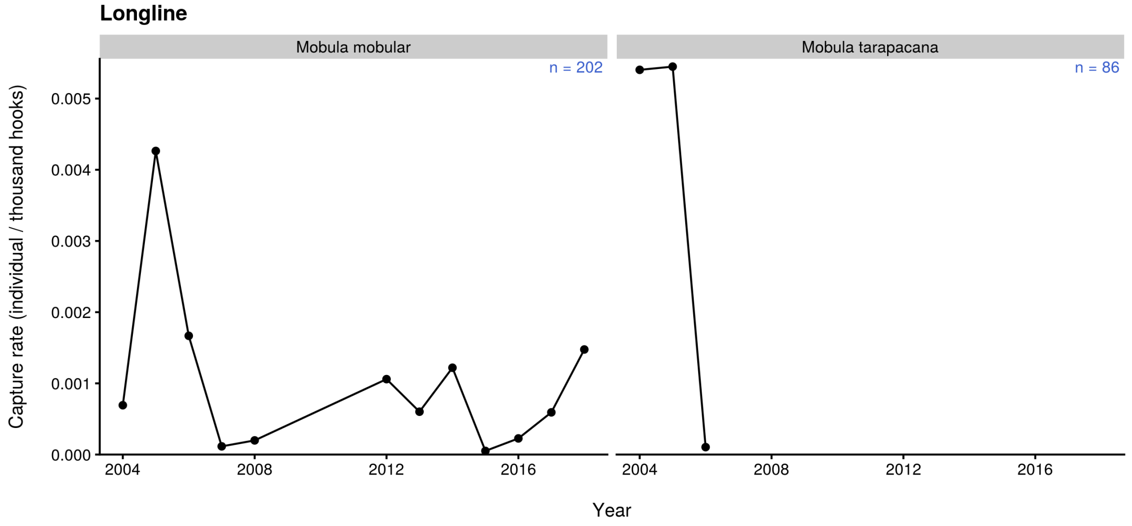

Figure A-2: Catch-per-unit-effort in individual per thousand hooks for devil ray records identified at the level of species by longline observers. The number of observations is shown in the top-right corner.

APPENDIX B: Spatial distribution of CPUE for manta and devil rays

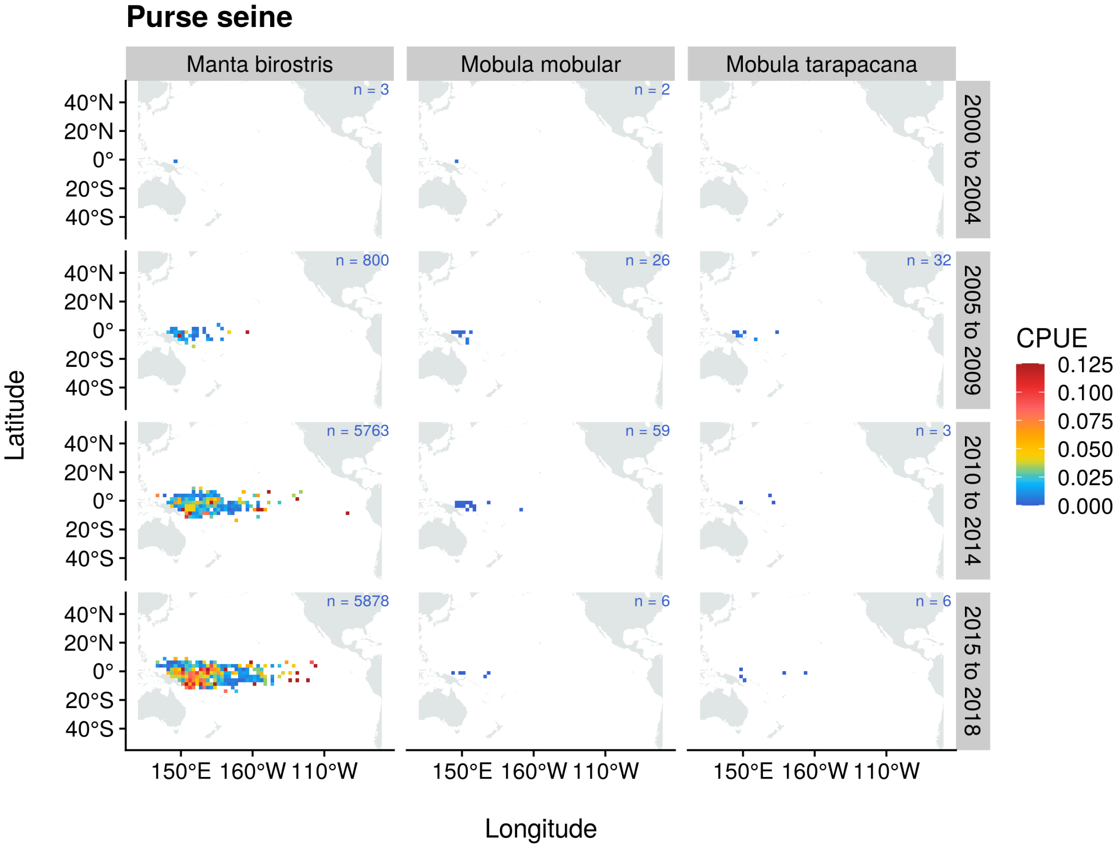

Figure B-3: Spatial distribution of catch-per-unit-effort (CPUE) for manta and devil rays by time period in observed purse-seine sets, with CPUE in individuals per thousand sets scaling from low in blue to high in red, and only retaining records at the species-level. Only species with a least 25 observed captures are included.

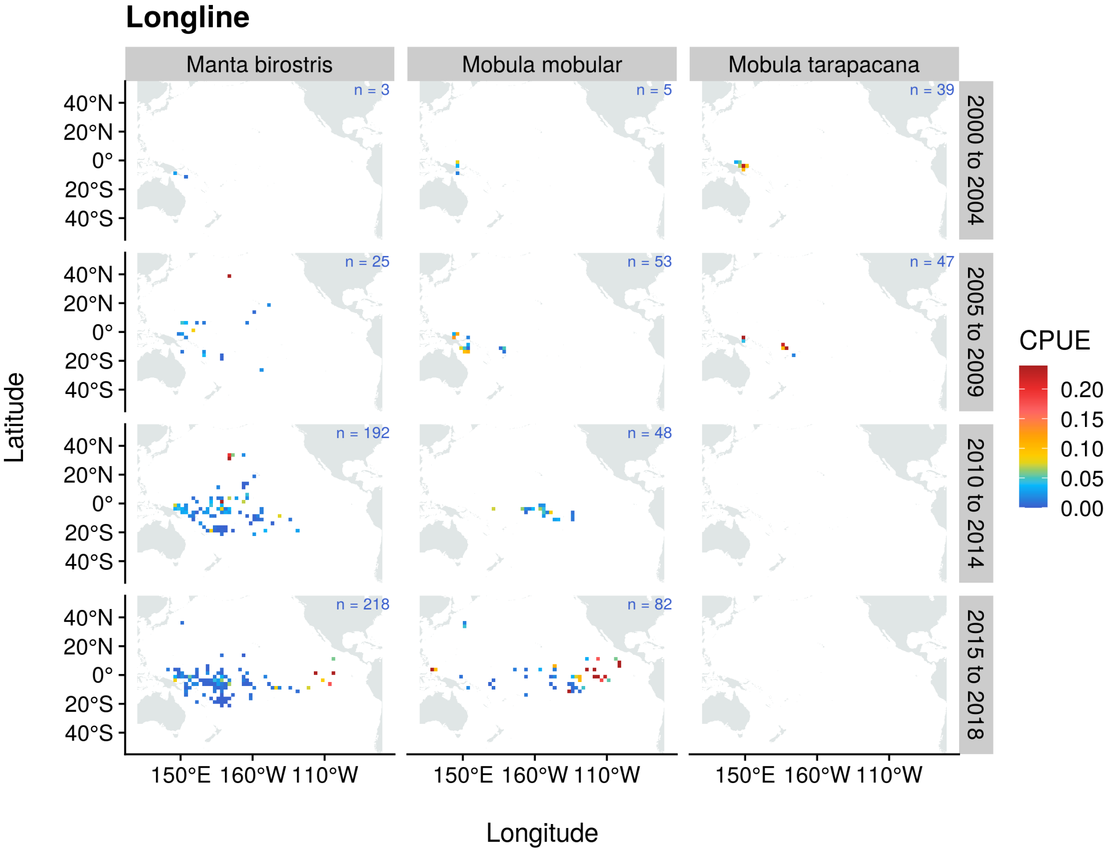

Figure B-4: Spatial distribution of catch-per-unit-effort (CPUE) for manta and devil rays by time period in observed longline sets, with CPUE in individuals per thousand hooks scaling from low in blue to high in red, and only retaining records at the species-level. Only species with a least 25 observed captures are included.