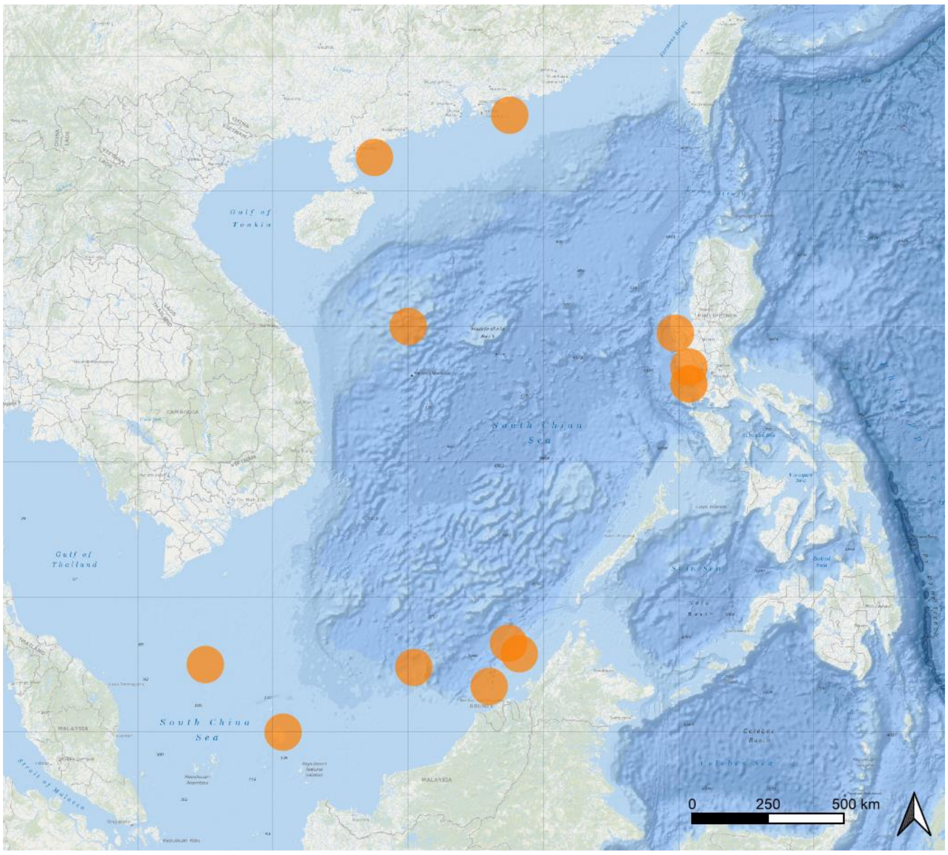
The CFRA: A Joint Assessment of South China Sea Skipjack Tuna Stocks



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Abstract

Katsuwonus pelamis, listed in the United Nations Convention on the Law of the Sea (UNCLOS) as a highly migratory stock, is a South China Sea species that is fished heavily by rival claimants. Political disputes over sovereignty claims have made joint fisheries management difficult, if not impossible. The absence of a regional fisheries management organisation (RFMO) in the South China Sea further compounds this difficulty. As a result, no authoritative collaborative stock assessment on this or other stocks in the South China Sea has been carried out in recent years. New efforts by fisheries scientists from China, Indonesia, Malaysia, the Philippines and Vietnam to develop a Common Fisheries Resource Analysis (CFRA) of *katsuwonus pelamis* in the South China Sea therefore represents a significant development in both regional science and regional cooperation. Using the Length-Based Spawning Potential Ratio (LBSPR) methodology, this paper examines the stock health of *katsuwonus pelamis* in the South China Sea. This delivers increased evidence to support domestic fisheries policymaking and develops norms and standards for regional cooperation.

Introduction

South China Sea Fisheries

The South China Sea (SCS) covers an area of about 3.8 million km^2 and forms the coastline of many countries and territories that are home to two billion people. In the south, it overlays the shallow (<200 m) Sunda Shelf encompassing hundreds of coral reefs, atolls and islands, while to the north, it extends over oceanic depths (>5,000 m). The SCS is one of the world's top five fishing grounds, producing roughly 12% of the global wild catch caught, amounting to roughly 20% of East Asia's total seafood production. Regionally, it provides food security, economic and social benefits to tens of millions of people (Teh et al. 2019; Sumaila et al. 2021). Despite its regional and global significance, knowledge of the SCS's diverse marine fauna and fisheries remains sparse, and the scale and severity of the sustainability crises it faces has not received the global attention deserved, at least in part, because they are so poorly documented (Sumaila et al. 2021).

Historically the SCS has been characterized by its many small-scale, poorly-regulated fisheries, which are categorized as IUU (Illegal, Unreported and Unregulated) due to their low level of regulation, and record keeping. Recent analyses of such records, as do exist, suggest that in aggregate the multitude of small-scale SCS fishers exert immense fishing pressure (Wang et al. 2022), having depleted total fish stocks by 70–95% since the 1950s, and 66–75% over the last 20 years, well below levels that could optimize yields (Chang et al. 2020). Annual wild caught production from the SCS apparently peaked in 2003 and has been declining for two decades (Sumaila and Cheung 2015; Teh et al. 2019).

Cooperative South China Sea Fisheries Management Initiative

Contentions about sovereignty in the SCS have simmered since the 1940s, and in recent years the area has become a global flashpoint. After consultations in five SCS capitals, the Centre for Humanitarian Dialogue (HD), a private diplomacy organisation founded to prevent, mitigate and resolve armed conflicts and crises through dialogue and mediation began facilitating multilateral dialogues aimed at reducing tensions in the region. One facet of that dialogue convened a series of fisheries management workshops which brought together experts and officials from China, Indonesia, Malaysia, the Philippines and Vietnam to discuss cooperative strategies to promote the sustainability of SCS fisheries. Participants decided to undertake a "Common Fisheries Resource Analysis" (CFRA) through which scientists from all five countries would develop parallel resource assessments, in a manner that did not require data sharing (which is politically infeasible due to the regional sensitivities). The CFRA process was organized with the support of HD, which assisted with secretariat support, sourced independent technical expertise, and provided modest resources when new data needed to be collected.

Participants prioritised working initially with Skipjack Tuna (*Katsuwonus pelamis* or SKJ) because it is an economically valuable transboundary species, caught by all participating countries, and there was some existing data from most jurisdictions. The 1982 United Nations Convention on the Law of the Sea (UNCLOS) categorises SKJ as a Highly Migratory species, thereby imposing responsibilities on relevant states to "cooperate directly or through appropriate international organizations with a view to ensuring conservation and promoting the objective of optimum utilization" (UNCLOS, art. 64). During the final stages of this process, the participants shared their analysis of their own countries' data to forge a consensus on the overall status of SKJ stocks in the SCS.

Data-poor Fisheries Assessment

SKJ in the SCS are a classic data-poor species, by which we mean there is insufficient accurate time series data and biological information to support standard methods for modelling biomass trends (Prince & Hordyk 2018). For example, even the magnitude and trends in SKJ catches are uncertain. The Southeast Asian Fisheries Development Center (SEAFDEC) compiles annual catch estimates for the UN's Food and Agriculture Organisation (FAO) statistical Areas 61 and 71 of the Western Central Pacific Ocean (WCPO), which include, but extend far beyond, the SCS. With those data, it is only possible to roughly differentiate fishing fleet catches of oceanic and neritic (coastal) tuna in the SCS. Williams and Lawson (2001) considered their estimate of the catch of oceanic tuna catch in the SCS during 1997, <10,000 mt, or < 0.4% of the total WCPO catch, to be a gross under-estimate of the actual magnitude of catches.

Data-poor fisheries present specific challenges for stock assessment, and necessitate the application of simplified techniques to evaluate whatever information exists, or can be collected. Here we report on how the CFRA overcame the challenge of data paucity to develop an initial regional assessment of the SKJ stocks in the SCS.

Skipjack Tuna

SKJ are broadly distributed across the Pacific Ocean, inhabiting tropical to temperate waters from the equator to around 35° of latitude in the WCPO, and the broad continental shelves of the SCS provide highly productive habitats for SKJ and various other neritic tuna species (e.g. longtail tuna, frigate and bullet tunas). Along with the bigger bodied bluefin, yellowfin and bigeye tuna, SKJ are one of the principal market species of tuna, despite being of lower value than the larger bodied species caught in colder and deeper oceanic waters, and are caught in high volumes in the Atlantic, Indian and Pacific oceans. SKJ have been the main target for high-value commercial fisheries throughout tropical regions, accounting for approximately 58% of the global tuna catch. In Indonesia, for example, SKJ contributed to 47% of Indonesia total tuna catch from 2005 – 2014 (Moore 2020).

While UNCLOS categorises SKJ as an Oceanic and Highly Migratory tuna species, along with bluefin, yellowfin and bigeye tuna, they are the most coastal of those main tuna species, and to some extent, more ecologically similar to the smaller neritic species of tuna. Oceanographic studies have found that SKJ migration, distribution and abundance are linked with meso-scale features, frontal systems and eddies, that form along shelf-breaks (Zainuddin et al. 2017). Revising his earlier conclusion that SKJ populations mix freely at broader scales population structure, Fujino (1996) concluded that the geographical genetic heterogeneities observed could only be explained through a combination of isolation by distance, and homing to local spawning areas. Subsequent research continues to suggest that most SKJ exhibit some degree of fidelity to regional and local spawning areas, so that SKJ stocks are effectively meta-populations, comprised of loosely connected locally spawning populations (Moore et al. 2020). While some level of gene flow across regionally scaled meta-populations and ocean basins is maintained by individuals occasionally undertaking broad-scale movement and/or some degree of larval dispersal, genetic differentiation is still correlated with distance between component populations. Thus, the SKJ stocks of the SCS likely comprise a meta-population with relatively independent local populations distributed along its coasts and shelf breaks. SKJ stocks of the SCS are therefore connected sufficiently to remain genetically similar, but possibly insufficiently connected to prevent the serial depletion of component stocks by concentrated fishing pressure close to the main population centres and largest markets.

Methods

The broad aim of the CFRA was to assemble a regional perspective of the SKJ resource in the SCS, from existing or easily collected data, to enable comparable parallel national analyses with a standard methodology. The CFRA began by surveying the data sets available to participating fisheries scientists in each country and concluded that data on the size composition of catches was the only form of data universally available, or that could be feasibly collected during the project's life-span. After consulting with independent international experts in small-scale fisheries assessment, the data-poor assessment methodology called length-based assessment of spawning potential ratio (LBSPR) (Hordyk et al. 2015a, b; Prince et al. 2015a) was selected as being the simplest, the most informative and the most feasible.

Length-based spawning potential ratio assessment

LBSPR assessment was specifically developed for fish stocks for which only data on catch size composition can feasibly be collected (Hordyk et al. 2015a, b; Prince et al. 2015). The methodology estimates the spawning potential ratio (*SPR*) of a population, which is a metric developed during the 1970s to indicate the risk of the future supply of young fish into the population (recruitment) declining, and so whether parental stocks are likely to be declining, stable or increasing (Mace 1994). Left unfished, fish complete their full life span and complete 100% of their natural reproductive (spawning) potential. By reducing the average life span of fish in a population, fishing reduces the reproductive, or spawning, potential of stocks below natural unfished levels (<100%). *SPR* is thus the proportion of the natural unfished spawning potential remaining in fished populations. The *SPR* concept is similar to the Human Reproductive Index (*HRI*), which is simply the average number of children per couple that survive to adulthood. With 2.1 children surviving through to adulthood, human couples replace themselves and those around them without children, ensuring population stability. An *HRI* above 2.1 ensures population growth, an *HRI* below that results in populations declining.

The metric of SPR is accepted internationally as a gauge of fisheries sustainability. 20% SPR is regarded as the replacement level, equivalent to *HRI* = 2.1, and is used as a Limit Reference Point (LRP) which stocks should be prevented from falling below of. *SPR* = 30-40% is used as a target range likely to optimize long term yields, and *SPR* ~50% indicates a level likely to optimise economic returns from a fishery (Mace 1994).

The LBSPR algorithms use the catch size composition to estimate SPR and relative fishing pressure (*F/M*, where *F* is 'fishing mortality', and *M* is 'natural mortality'). Essentially LBSPR compares the size of the fish in the catch with the size at which they reach sexual maturity (L_m). If fish are all caught before becoming adults, their populations have little or no spawning potential (~ *SPR* 0%). On the other hand, with low fishing pressure, fish are likely to survive to grow to maximum, or asymptotic, sizes (L_∞) and fulfil *SPR*~100%.

Weight of Evidence Evaluation of Data-poor Fisheries

The LBSPR methodology is a simplified form of assessment developed for data-poor fisheries that lack most of the information necessary to develop assessments of biomass trends. Prevented by the data-poor context from developing any form of model for biomass trends, we applied LBSPR to the available data and interpreted the results, within the context of the data collection process, with a weight of evidence approach. For this analysis the algorithms needed by participating fisheries scientists in each country to apply the LBSPR methodology were accessed through the website http://barefootecologist.com.au.

Input Parameters

The data inputs required for the LBSPR methodology are:

1. Catch size composition data that are indicative of the size of the adult fish in a population. If the type of fishing being conducted fails to catch the largest size classes of a fish species, then the estimate of *SPR* produced for that species will be too small.
2. Estimates of the size at which fish become adults (L_m) which is defined by L_{50} and L_{95}, the sizes at which 50% and 95%, respectively, of a population are observed to be mature.
3. The two life history ratios (LHR) that characterise differing taxa and which determine the relative shape of population size and age compositions (Hordyk et al. 2015a). The LHR are:
    a. L_{50}/L_∞ - the relative size of maturity being the size of maturity (L_{50}) divided by the average maximum size individuals might attain if they survived to infinite age (L_∞); and

b. M/K - the rate at which a cohort of fish dies off from natural causes, divided by the von Bertalanffy growth parameter (K), which is the annual rate of grows to L_∞.

The first two of these data inputs (catch size composition and local L_m estimates) need to be estimated locally for each fish species because they vary from place to place. The LBSPR methodology is based on the simplifying assumption that the assessed populations exist in a relatively stable, or 'equilibrium' state, so that size compositions are expected to change relatively slowly, over the life-span of species. Consequently, it is valid to analyse size composition data aggregated over several years.

Life History Ratios

The LHR define the shape of adult size compositions relative to size of maturity (Hordyk et al. 2015a) and are similar across species complexes, genera and families (Holt 1958; Prince In press). They are best estimated generically from high quality published age and growth studies by species, if sufficient high-quality studies exist, but that rarely being the case, the best estimates are normally derived for entire families due to the larger number of age and growth studies available at that level of aggregation (Prince In press).

Based upon a meta-analysis of high quality and standard controlled parameter Prince et al. (In Press) estimate for the family of Scombridae:

M/K = 0.99 (n = 90, SD = 0.46)

L_m/L_∞ = 0.65; (n = 39, SD = 0.14)

Limiting the sample within that meta-analysis specifically to SKJ age and growth studies we estimate:

M/K = 1.10 (n = 6, SD = 0.45)

L_m/L_∞ = 0.69; (n = 4, SD = 0.10)

By comparison Vincent et al. (2019) derive 'best estimate' of the individual life history parameters (LHP; M, K, L_m, L_∞) for using within the Western Central Pacific Fisheries Commission (WCPFC) SKJ stock assessment with which we can infer:

M/K = 1.11

L_m/L_∞ = 0.59

Taken together, this body of information suggested a plausible range of LHR estimates, and we used the following matrix of 12 sets of input assumptions with each datasets analysed:

M/K = 1.0, 1.05, 1.10, 1.15

L_m/L_∞ = 0.60, 0.65, 0.70

Size of Maturity

Growth and size of maturity in marine species is related through levels of dissolved oxygen to ambient water temperature (Brown et al. 2004, Pauly 2010), with species in colder water with higher oxygen content growing more slowly, but to larger maximum sizes, and maturing at proportionally larger sizes, than in warmer water – a relationship which is apparently observed in SKJ around this region.

Ohashi et al. (2019) estimated SKJ L_{50} in the WCPO varying from ~60 cm in the temperate region, through 54.5 cm in the sub-tropical, to ~50cm in the tropical region north of Papua New Guinea (PNG). These estimates of L_{50} in the more oceanic environment of the WCPO contrast with smaller unpublished Vietnamese estimates (L_{50} = 40.9cm; L_{95} = 45.0 cm), based on a sample of 339 fish caught in 2018 during fishery independent surveys (FIS) (Unpubl. Data; Tran Thi Ngoc Anh, Research Institute for Marine Fisheries). We confirmed that analysis using a larger dataset (n = 14 383) from the Vietnamese FIS 2000 – 2005, and inferred that the SKJ caught in the more oceanic (and we presume) cooler environment of the WPCO mature, and grow to larger sizes than in the shallower (and we presume) warmer waters of the SCS. In this context our preferred assumption for analysis has been L_{50} = 41 cm; L_{95} = 45 cm, but with some of the datasets we also explored the range of Ohashi et al.'s (2019) estimates.

In this context we note, that the L_m/L_∞ = 0.59 implicit within the Vincent et al. (2019) WCPO assessment, actually combines Ohashi et al.'s (2019) smaller tropical size of maturity estimate, because most of the WCPO catch is tropical, but combines it with a larger subtropical region growth curve. If instead we match the subtropical region growth curve with size of maturity estimates for the same region, we estimate L_m/L_∞ = 0.64, which is closer to the average derived through meta-analysis, and affirming of our choice of L_m/L_∞ = 0.60 as the bottom bound of plausible values.

Size selectivity:

A critical assumption of the original formulation of LBSPR assessment used here is that the size composition data analysed are representative of the size composition of the adults of the stock being assessed. To the extent adult size classes are under-represented, *SPR* will be under-estimated and *F/M* over-estimated.

All fishing is selective with respect to the size and age of the fish that are caught (Holt, 2014); the term “size selectivity” refers to the size range vulnerable to being caught by any type, or combination, of fishing methods. The physical characteristics of fishing gear (e.g. mesh and hook size), are important determinants of size-selectivity, along with how, when and where fishing occurs. Size and age-related behaviours, feeding patterns, and depth distributions may all influence size-selectivity of fishing. SKJ are caught with a wide range of fishing gears, from inshore waters where juvenile size classes are most prevalent, to offshore waters where adult size classes are more common. They may be the main species targeted by fishers, or simply caught incidentally while targeting other species. Consequently, a wide range of size-selectivities are observed in catches. In applying LBSPR to SKJ data, the size selectivity of the gear/s used to take the catches being sampled must be taken into account when interpreting results.

The WCPFC Vincent et al. (2019) assessment of SKJ stocks contains explicit assumptions about age, and thus size, selectivity for the fishing gears described by their assessment models, some of which have specific relevance to our study. In general, catch compositions from fishing with long-lines, drifting gillnets and trolling tend to provide the best representation of adult size classes. Catch compositions from purse seining, pole and line, and inshore fishing with hand-lines, which the WCPO categorise as ‘small-scale inshore fisheries’, typically under-represent adult age and size classes. Fishing with light lift-nets, sampled by this project, is not considered by the WCPFC modelling, but has been shown by sampling by Wu et al. (2016) to select small juveniles.

Ideally in applying LBSPR, the length composition of the total catch would be used, in reality landings data rarely exist in sufficient detail to make that feasible, and varying size composition data from different types of fishing must be used, resulting in a range of results that require interpretation. Pon’s et al. (2019) demonstrates that the most accurate estimates of *SPR* and *F/M* are produced by selecting the catch composition of fishing that provides the best representation of the adult size classes.

Results

Vietnam

The Research Institute for Marine Fisheries, under the Vietnamese Ministry of Agriculture and Rural Development, provided access to a range of size composition data from purse seine and gillnet fisheries in the Central and Southeast Fishery Areas (6 – 16°N and 106 – 112°E), as well as from FIS conducted through those fishing grounds and data collection programs described by Vinh et al. (2021). The fishery dependent data were collected monthly during 2016-17 in 9 main ports. The sampled landings were primarily from the purse seine fishery (~60%) which uses small mesh sizes (20-30 mm), but also (~40%) from a drifting gillnet fishery which mainly used 100 mm stretched mesh size.

Purse Seine Catch

The SKJ caught by purse seining (*n* = 104 570), ranged in size from 16 ~ 66 cm, but were primarily comprised of 35 - 50 cm size classes. The adult size classes (>40cm) are poorly represented, and SL_{50} is estimated to be well below the size of maturity (SL_{50} ~38cm) (Table 1). Across our range of the input assumptions, very low estimates of *SPR* (5-15%) resulted. Taking advantage of the large sample sizes, these data were also analysed by quarter producing similar results.

Gillnet Fishery Catch

The gillnet fishery (*n* = 93 957) landed a greater proportion of larger size classes, sizes ranged from 24 - 68 cm, but were primarily comprised of 35 - 60 cm fish. Across our range of input assumptions, average SL_{50} ~ 41cm was estimated to be similar to assumed L_{50}, and average *SPR* = 0.27, with a range 0.15 – 0.43. Analysis by quarter using the same range of input assumptions produced a slightly narrower range of estimates, *SPR* = 0.21 – 0.31.

Fishery Independent Surveys

The Vietnamese FIS are conducted each year during Oct. - March and April - Sept, with drift gillnets being set at 60 fixed stations across the SKJ fishing grounds. A range of stretched mesh sizes (73, 85, 100, 123mm) are used with the aim of imposing a logistic (S-shaped) form of size-selectivity on samples, and select SKJ equally across all adult size classes. We analysed FIS data from two periods 2000-02 (*n* = 7 851) and 2003-05 (*n* = 6 531), separately at first, then due to their similarity, together in aggregate. The size of fish sampled ranged from 20 - 84 cm, and were primarily comprised of 40 - 58 cm fish. The average SL_{50} ~ 43cm is estimated to be marginally larger than L_{50}, with average *SPR* = 0.35 with range 0.20 – 0.50. Slightly higher than estimated with the gillnet fishery data.

Philippines

The Philippines' National Fisheries Research and Development Institute, under the Department of Agriculture, provided data collected through the National Stock Assessment Program 2014 – 2018 in two regions; region 1, off the north-western corner of the Philippines extending from Bangui Bay (18.6°N; 120.7°E), to Dasol Bay (15.9°N; 119.8°E) and out to Scarborough Shoal (15.1°N; 117.5°E); and Region 3, the Zambales Coast (14.8°N; 120.3°E), the adjacent west coast to the south of Region 1, closest to Manila.

Region 1

The Region 1 dataset (*n* = 46 325) is large but noisy. It contains data from 17 types of fishing gears, for many of which the sample sizes are too small to be useful. We analysed the larger subsets of data; two of which comprising ~36% of the samples; handline (*n* = 15 654), multiple and purse seine (*n* = 1 201) contained few of the adult size classes, and produced small estimates of average SL_{50} ~31 – 33 cm, as well as low *SPR* ~ 0.03 - 0.09 (Table 1). Samples from two gear types, comprising ~47% of the samples – troll line and floating hook & line – contained a higher proportion of adult size classes.

Floating Hook & Line

Floating hook and line describe an inshore version of oceanic long-lining, involving shorter centre lines, each with just tens of hooks rather than hundreds and thousands. The catch of the floating hook and line fishery (*n* = 5 965) has a size range 20 - 82 cm, but primarily comprised of 35 - 55 cm individuals. Using our range of assumptions, we estimated average *SPR* ~ 42% (range: 0.23 – 0.65); with average SL_{50} ~ 36 cm, slightly smaller than the size of maturity.

Troll Line

The catch of the troll line fishery (*n* = 15 036) has a size range 25 - 82 cm, but primarily comprised of 35 - 55 cm individuals. Applying our range of input assumptions, we estimated

SPR ~ 0.45% (range: 0.24 – 0.72); with average SL_{50} ~ 38 cm, also slightly smaller than size of maturity.

The length frequency data from both the floating hook and line and troll fishery are characterised by having a numerically small secondary mode at 60 - 75 cm, in addition to the distinct main mode at 35-55 cm. The LBSPR model fitted this secondary mode poorly, smoothing the fitted uni-modal curve across the two observed modes, and under-predicting the abundance of the ~45 - 50 cm, 55 - 60 cm, and >65cm size classes. These secondary modes could possibly be interpreted as being comprised of larger maturing individuals observed by Ohashi et al. (2019) in the adjacent Sub-tropical region of the WCPO. Alternatively, it may be an artifact of these noisy data, perhaps resulting from the mis-attribution to SKJ of other larger bodied tuna species in samples. In either case, this feature of these data weakens our confidence in these results.

Region 3 All gears

The quality of the data (n = 40 341) for 14 types of gear in Region 3 was better than for region 1, but unfortunately it contained no data for the gear types expected to catch adult SKJ. We analysed data from; handline (*n*=10 817), multiple handline (*n*=10 257), and hook and line (*n*=1 810), all of which predictably produced low SPR estimates (0.03 – 0.06) and low estimates of size selectivity (SL_{50} ~ 36 cm).

Indonesia

Unable to find existing Indonesian data for the southernmost extent of the SCS (FMA 711) the CFRA initiated research by the Raja Ali Haji Maritime University, which ascertained that small catches of SKJ were landed onto the Natuna Islands (4.0^{o}N; 108.25^{o}E) in the Tudjuh Archipelago, in the Riau Islands Province, off the northwest coast of Borneo. Size composition sampling occurred in three local markets, Natuna, Anambas and Pemangkat. The type of gears used to make these catches is not known with certainty, but SKJ are known to be caught locally by trolling (*rawai*) and inshore set-lines (*tonda*) which we assume is similar to the Philippines' 'floating hook and line'. We initially analysed the data from all three markets in aggregate (*n* = 1 263), but the model does not fit the data convincingly, probably because of the mix of catches from a range of gears with varying size selectivity. Consequently, we focussed the analyses on the data collected from Pemangkat (n = 754) assuming it provides the 'best' indication of the size composition of the adult SKJ stock in the area. The model still produced a somewhat unconvincing description of the data, missing the modal value, failing to predict the left-hand side of the distribution, and estimated size selectivity to be unrealistically high (SL_{50} = 53 cm, SL_{95} = 62cm) (Table 1). Across our range of input assumptions, we estimate average SPR = 0.32 (range 0.19 – 46)

Constraining the analysis to focus on the assumed sub-adult and adult size classes by truncating size classes <36cm resulted in a slight reduction in sample size (n = 725), improved the model's prediction of the right-hand side of the curve, but produced similar estimates.

Malaysia

The CFRA was given access to data for 699 SKJ sampled during 2014 – 2018 by the Department of Fisheries, Malaysia through their routine biological monitoring of the catch of oceanic tuna landed into Labuan and Kota Kinabalu, in Sabah (5.30^{o}N; 115.24^{o}E). The sampled SKJ were the bycatch of a handline fishery that principally targets yellowfin tuna around fish aggregating devices (FADs). Most of the SKJ landed into Malaysia are in fact taken through targeted fishing with purse seines, but we did not analyse data from that fishery. We assume it would have a similar size composition as the purse seine data from other co-operating countries. The adult size classes were relatively well represented in this sample, which had a size range of 27.0 - 73.4 cm, but was primarily comprised of 35 - 60 cm fish. There is the appearance of some multi-modality around 40, 50 & 60 cm, but its regularity and coincidence with tens of cms suggest that that may possibly be an artifact of measurement rounding. The size of selectivity was estimated to be smaller than the assumed size of maturity. (SL_{50} ~35cm cf L_{50} ~41cm). With our range of assumed input assumptions, we estimate average SPR= 0.41 (range 0.22 – 0.66).

China

In China, the CFRA collaborated with the Fisheries College of Guangdong Ocean University, a key university co-developed by the People's Government of Guangdong Province and the State Oceanic Administration. Fisheries scientists interviewed skippers and examined electronic fishing logs. Only catches of SKJ being landed by Light falling-netting vessels could be sampled. The Light falling netting vessel use strong lights to lure feeding pelagic squid and fish to vessels, before dropping a small mesh net over the aggregation of feeding juvenile fish and squid. The CFRA was informed that there had been negligible landings by purse seine or other methods over the previous decade.

Catches of SKJ were sampled from:

1. Northern SCS, (21.00 - 22.25ºN and 111 – 115ºE), **121** individuals from 2020 to 2021, sampled at the main ports.
2. Spratly Islands sea area (10.4 - 14.6ºN and 112 – 115ºE), SI **1057** individuals from 2014 to 2018, sampled on boat.

Due to the poor condition of sampled catches, lengths were measured from the tip of the snout to the posterior end of the last vertebra, which is different to the fork length measurement used by other studies of SKJ. We applied a conversion factor of 1.05 to make these measurements equivalent to the Fork Length used elsewhere in this study.

The size range of SKJ was 11 ~ 52 cm, although primarily comprised of 20- 26 cm, juvenile size classes. Adult size classes are almost entirely absent from these samples and predictably these data produced low estimates of the size of selectivity (SL_{50} ~39cm) and *SPR* = 0.09.

Discussion

Catch Size Compositions

The catch size composition data collated through our collaboration have been categorised as coming from:

1. Gears with dome-shaped size selectivity, so that catches contain few adult sized fish and are unrepresentative of adult size classes. In this category, we have placed samples from the purse seine fisheries, handline, multiple handline, light fall netting; or
2. Gears with basically logistic forms of selectivity, that provide representation of adult size compositions. In this second category we place the drift gillnets, floating hook and line, trolling, the Malaysian by-catch from handlining for yellowfin tuna, and the catch from Natuna Islands markets (which were probably caught by trolling).

Based on the assumption that the shape of the size frequency histograms on their right-hand, terminal side is determined simply by growth, and mortality from fishing and natural means, the LBSPR technique can only be used with the second group of size compositions data to evaluate the relative fishing pressure (*F/M*) experienced by these adult size classes, and the *SPR* of populations. To the extent that the right hand-side of the length frequency histograms from the first group of fisheries are determined by dome-shaped selectivity, estimates of *SPR* or *F/M* derived from those data will be biased low and high, respectively, and inutile for informing that aspect of our assessment. Nevertheless, the estimates of the size selectivity of the smaller fish in the catch derived from the analysis of catches caught with dome-shaped selectivity can still inform our broader 'weight of evidence' diagnosis of the SCS fisheries for SKJ.

The *SPR* estimates from the gear types we assume have some form of logistic selectivity produced relatively similar estimates across the region, which taken at face value could suggest that while subject to relatively high fishing pressures (*F/M* = 0.87 – >5.0) the SKJ stocks retain *SPR* levels (*SPR* = 0.27 – 0.42) that remain around or a little below, generally accepted reference points for sustainable management (i.e. *SPR* = 30-40%; *F/M* = 0.8 – 1.0), and above the internationally accepted LRP of *SPR* = 20%. Taken in isolation these results suggest the fishing pressure on the adult portion of the stock could be sustainable.

We are, however, cognisant of the fact that our assessments only provide an indication of fishing pressure and survival during the later adult stage of the SKJ life cycle, rather than an assessment of fishing pressure over the entire life cycle of the stock. Applying LBSPR assessment, as we have, to data from the gears with logistic size selectivity similar to L_m, implicitly assumes that the juvenile size classes are protected until that size, although the entirety of our samples show that the catch of smaller juvenile size classes is numerically greater than that from the gears targeting larger juvenile and adult size classes. These observations raise the issue as to the extent to which we are over-estimating the SPR of the SCS SKJ resource, and whether the survival of juvenile SKJ is sufficient to sustain the adult portion of stocks. If cohorts are heavily depleted as juveniles, so that few survive to adulthood, subsequent light or moderate fishing upon depleted adult size classes can contribute little to sustaining recruitment. In this scenario our estimates of SPR and survival through adulthood do not give a true indication of the stock depletion occurring through the removal of juvenile size classes.

This confronts us with the limitations of the LBSPR methodology, imposed upon us by the paucity of data, and the lack of detailed biological studies. Determining the effect of fishing on the biomass of juvenile size classes, and its likely impact on recruitment rates, would require accurate, spatially explicit time series data on catch and abundance for the broader SCS over several decades, as well as detailed understanding of the spatial structure of the resource, estimates of natural rates of mortality by size / age class, and all the other biological parameters needed to support detailed biomass modelling. That sort of sophisticated assessment would require long term and expensive studies that were clearly beyond the scope of this study, and are unlikely to ever be possible while the current socio-political circumstances persist. With the scant data available to us, and the simple method that necessitated, we cannot adequately address this issue here, but only hope to identify and raise its profile with simulations based on our results.

Definitions of Overfishing

Fisheries science recognizes two distinct forms of overfishing, that while closely linked, do not necessarily occur simultaneously. The first, growth overfishing, wastes potential yield by catching fish before they fulfil their potential for weight, or biomass, growth. The second, recruitment overfishing, results from catching fish before they complete sufficient spawning potential to replace themselves, and continued recruitment overfishing drives the long-term decline of populations into local extinction. The depletion of resources commences with growth overfishing, which is always sub-optimal, but may be sustained until recruitment overfishing occurs. While the size composition of the catch is $> L_m$, recruitment is likely to remain stable and high, but as fish are increasingly caught at sizes $< L_m$, prior to reproducing, recruitment and growth overfishing begin operating together to drive the serial depletion of resources. Because cohorts of fish achieve their optimal biomass around L_m, targeting size classes of fish $< L_m$ implicitly involves growth overfishing, sub-optimal yields and the risk of recruitment failure.

Simulated Purse Seine and Gillnet Fisheries

Using the simulation framework found at http://barefootecologist.com.au/YPRsim with our estimates of size of selectivity, we have simulated the SCS SKJ fishery as if it were exclusively fished with either purse seine (figure 4) or drift gillnets (figure 5). With both scenarios we assume a relatively productive stock recruitment relationship for SKJ with relatively high steepness (h=0.7). These simulations illustrate how by changing the relationships between F/M, SPR and potential yield, the smaller size selectivity of purse seining reduces the resilience of the resource to growth and recruitment overfishing. For each fishery the size selectivity, relative to size of maturity, is depicted in the top right panel of both figures. With the purse seine fishery (figure 4) the size of selectivity is smaller than the size of maturity ($SL_{50} < L_m$), while with the gillnet fishery (figure 5) the size of selectivity is similar to the size of maturity ($SL_{50} \sim L_m$). In the bottom left-hand panels the size of selectivity and maturity is plotted relative to the SKJ SCS growth curve. With the smaller size of selectivity of purse seining (figure 4), the potential yield curve (blue curve in the bottom right-hand panel of both figures) is narrower, and potential yields are optimised over a narrow band of relative fishing pressure (F/M = 0.5 – 1.25 cf. 0.5 – 3.5). With purse seining relative yield, SPR and spawning biomass can be greatly reduced by high levels of relative fishing pressure (F/M < 2.0) due to the combined impact of growth and recruitment overfishing. In contrast with $SL_{50} \sim L_m$ (figure 5) the fishery is made resilient to recruitment overfishing, so that potential yields are optimised over a broader range of relative fishing pressure, and significant loss of potential yield is prevented within the simulated range of relative fishing pressure. The slight decline in potential yield observed in the simulation is being lost through growth overfishing alone. Thus, fisheries with $SL_{50} \sim L_m$ may be managed less rigorously than fisheries targeting juvenile size classes. Fisheries with $SL_{50} < L_m$ must be managed effectively at lower levels of fishing pressure (F/M) if yields are to be optimised and recruitment overfishing prevented.

Symptoms of Overfishing

In this context our study produced various qualitative observations that amplify our concerns for the status of SKJ stocks, and SCS marine resources in general. The depletion of fish stocks is typically accompanied by symptoms that are familiar to fisheries scientists, which include:

1. The ‘race for the fish’ through which fishers, regions and nations respond to the depletion of larger size classes and parental biomass by intensifying competition with each other, fishing harder, and deploying new techniques for targeting smaller fish earlier in the life cycle of species (Rosenberg 2017).
2. Depletion profiles centred on major ports, markets and centres of population, where fishing pressure first intensifies, before expanding sequentially along coastlines, island

chains, and out into oceanic waters, resulting in the serial depletion of component stocks, within broader scaled meta-populations (Prince & Hilborn 1988).

3. The fishing down food webs by suites of fisheries and gears types, which begins by the targeted depletion of the largest bodied most valuable individuals and species, and progresses towards smaller, less valuable species and juveniles, and less targeted forms of fishing (Pauly et al. 1998).

Many facets of the SCS SKJ fishery are suggestive of these symptoms of overfishing:

The Race for Fish and Fishing Down Food Web

The evolution of the fishing gears used to catch SCS SKJ is suggestive of the race for fish and fishing down of the food web. Chee (1992) describes the replacement at that time of artisanal fishing techniques such as handlining, trolling and coastal barrier nets by industrial purse seining and drift gillnetting. Techniques which in turn are now being replaced, at least in the north of the SCS, by biomass fishing to produce fish-meal (Pauly and Chuenpagdee 2003; Teh et al. 2019). The latest development in that regard being fishing at night with lights and fine mesh lift nets for purple-back flying squid (*Sthenoteuthis oualaniensis*) along with small juveniles of SKJ, *Thunnus albacares*, and *Decapterus maruadsi* which together comprise 35-40% of landings (Wu et al. 2016).

Serial Depletion or Nursery Grounds

Some aspects of the data we gathered also suggest serial depletions are occurring within this fishery. For example, with the Philippines' data we observed that closest to Manila in Region 3 the substantial data-base contained no data for fishing methods likely to catch adult fish. We only found data from fishing methods that target larger juvenile and adult size classes from the more remote Region 1. In parallel to that observation; we were unable to attain samples of any catches containing adults from China. The anecdotal accounts we gathered suggest that in that region of the SCS, even purse seine catches have declined to low levels over the last decade, and we could only sample catches for light lift netting. Such observations are consistent with the pattern of serial depletion we expect in depleting fisheries.

An alternative explanation that was advanced is that there are only SKJ nursery grounds closer to the Chinese mainland, from which catches of adult SKJ were never expected. That argument could also be used to explain the lack of adults catches in the Philippines' Region 3 data. Our limited snap-shot study is insufficient to refute that explanation, however, other studies have not recognised the existence of regionally segregated nursery grounds as a feature of SKJ stock structure (Moore et al. 2020).

The Need for Effective Multi-National Fisheries Management

Focussed on national development instead of environmental sustainability, countries in the SCS region have seen decades of uncontrolled coastal development. The SCS is the sea with the greatest subsidization of fishing fleets, estimated at 1.89 billion USD in 2009, some 31% of the global total. Of the 3.2 million fishing vessels operating in marine waters worldwide, over half operate in the SCS and the East China Sea (Sumaila and Cheung, 2015). This region-wide subsidisation of fisheries has driven overcapitalization and resulted in regional overcapacity in fleets, effectively funding the continued over-exploitation of depleted resources (Milazzo 1998; Sumaila et al. 2010). In itself the subsidisation of SCS fisheries is a clear indication of ineffective regional management and the need for that to change.

This is in contrast with the trend in world fisheries towards improving the sustainability of fisheries by reducing fishing pressure, developing selective fishing gears to target the most valuable species and size classes, as well as minimizing the catch of by-catch and non-saleable 'trash species'. With the development and escalation of 'biomass fishing', fishing pressure in the SCS continues to intensify and become less selective (Teh et al. 2019).

The expansion of aquaculture globally is helping to fill the gap between supply and demand for fish, and contributing to economic development in the region via exports. The production and use of fish for fishmeal has grown especially important through East Asia, which now accounts for ~62% of global aquaculture production. Five of the top ten global aquaculture producers in terms of both quantity and value are countries in the SCS region (China, Vietnam, Thailand, Indonesia and the Philippines), with the first three accounting for 56.9%, 10.4%, and 27.5%, respectively (Teh et al. 2019). But at some stage the supply of fish meal from wild fisheries will be limited by the capacity of wild ecosystems to supplying larval and juvenile fish to those 'biomass fisheries', and effective management will become necessary to sustain the potential yield from the parental stocks.

The effective management of SKJ will require all nations to first cap the fishing pressure on juvenile and adult SKJ to prevent further escalation, and then to work together to reduce the fishing of juvenile size classes, so as to make the stocks more resilient to growth and recruitment overfishing. This will be extremely challenging in the SCS context, where so many stocks overlap national boundaries and where a wide variety of fishing gears are used to harvest differing phase of life-cycles, impacting the catches of other gear types and countries. In the SCS context, fisheries management will always be intrinsically linked to the allocation of resources between fishing gears, within and across countries (Chee 1992). Yet, there is currently no permanent forum for the difficult dialogue required to develop the trans-national cooperation that will be necessary to facilitate effective fisheries management. In other regions, regional fisheries management organizations have been established as multi-national frameworks for facilitating the management of trans-boundary fish stocks. A similar framework is required in the SCS.

Conclusions

This study documents a novel approach to conducting basic fisheries studies with the explicit aim of reducing international tensions in a contested region by facilitating and informing international dialogue about resource management. Key to this initiative has been the simple form of science deployed, within a weight of evidence framework. While leaving much to be desired from the purely scientific perspective in terms of unambiguously diagnosing biomass trends, it still identifies overall trends that are important for policy makers. The LBSPR methodology proved accessible to all collaborators in evaluating the only universally available data, and has provided a semi-quantitative context for synthesizing the qualitative information accessed through this collaboration. Through this, it has enabled an inclusive international dialogue about SKJ stock status to be initiated.

On the basis of our studies, we conclude that of itself the fishing pressure targeted at the adult portion of the stock at the current time in most regions of the SCS, is probably sustainable. Our major concern is the unquantified (and probably heavy) fishing pressure on juvenile SKJ, with fishing gears that target SKJ and increasingly with gears that fish for multi-species assemblages of post-larval and early juvenile pelagic species. Un-managed, these fishing pressures are inevitably causing growth overfishing, and over some time period will cause recruitment overfishing, that may already be driving the serial depletion of component populations of a SCS SKJ meta-population. The sustainability of biomass fishing to supply the feedstock for aquaculture will ultimately depend on managing fishing pressure on both juveniles and adults at levels which provide for the maintenance of recruitment to all parts of the SCS SKJ meta-population.

To this end we recommend:

- Building on the CFRA of SKJ to regularise cooperation between government and non-government fisheries scientists among SCS coastal states. This cooperation would build a shared evidence base for cooperatively managing shared fish stocks.
- Updating domestic policy to address fishing pressure on juvenile and adult SKJ throughout the SCS to prevent further depletion.
- Intensifying international collaboration to identfiy cooperative measures to reduce fishing pressure on juvenile size classes.

Tables & Figures

Fishing Gears with Dome-shaped Size Selectivity

Country	Dataset	n - samples	n - scenario	Mean SPR	S.D. - SPR	Min. SPR	Max. SPR	Mean F/M	S.D. - F/M	Min. F/M	Max. F/M	Mean SL50	S.D. - SL50	Min. SL50	Max. SL50	Mean SL95	S.D. SL95	Min. SL95	Max. SL95
Philippines	1. Handline	15654	12	0.09	0.03	0.05	0.13	3.04	0.83	2.02	4.40	33.1	0.24	32.8	33.4	41.2	0.34	40.8	41.6
Philippines	1. Purse Seine	1201	12	0.03	0.01	0.02	0.05	4.54	1.03	3.28	6.30	30.9	0.21	30.7	31.3	41.3	0.26	41.1	41.7
Philippines	3. Handline	10810	12	0.06	0.02	0.03	0.09	5.27	1.32	3.67	7.45	36.7	0.17	36.5	36.9	47.4	0.17	47.2	47.6
Philippines	3. Multi. handline	10570	12	0.03	0.01	0.01	0.04	7.29	2.15	4.78	10.77	35.8	0.87	34.7	36.9	51.1	1.14	49.8	52.5
Philippines	3. Hook & Line	1810	12	0.06	0.02	0.03	0.09	5.82	1.44	4.07	8.21	37.0	0.11	36.8	37.1	44.5	0.12	44.4	44.7
Vietnam	Purse Seine	104570	12	0.10	0.04	0.05	0.15	4.11	1.23	2.65	6.12	37.9	0.33	37.5	38.3	49.2	0.39	48.8	49.7
China	Light Lift Net	35	12	0.07	0.02	0.04	0.10	7.51	1.69	5.45	10.32	38.2	0.01	38.2	38.2	40.2	0.01	40.2	40.2

Fishing Gears with Logistic Size Selectivity

Country	Dataset	n - samples	n - scenario	Mean SPR	S.D. - SPR	Min. SPR	Max. SPR	Mean F/M	S.D. - F/M	Min. F/M	Max. F/M	Mean SL50	S.D. - SL50	Min. SL50	Max. SL50	Mean SL95	S.D. SL95	Min. SL95	Max. SL95
Philippines	1. Troll	9037	12	0.45	0.17	0.24	0.72	0.90	0.51	0.26	1.69	37.6	0.43	37.1	38.2	44.1	0.63	43.4	44.9
Philippines	1. Floating H&L	3400	12	0.42	0.15	0.23	0.65	0.87	0.42	0.33	1.54	35.8	0.23	35.6	36.1	41.8	0.28	41.5	42.2
Vietnam	Gillnet	93957	12	0.27	0.10	0.15	0.43	2.17	0.91	1.03	3.56	40.8	0.53	40.1	41.4	48.5	0.81	47.5	49.4
Vietnam	FIS	14382	12	0.35	0.12	0.20	0.54	1.84	0.79	0.85	3.04	43.0	0.20	42.7	43.2	50.5	0.20	50.3	50.8
Malaysia	Hook & Line	699	12	0.41	0.16	0.22	0.66	0.94	0.49	0.32	1.71	36.6	0.31	36.2	37.0	40.5	0.55	39.9	41.2
Indonesia	Pemangkat	754	12	0.32	0.10	0.19	0.46	13.37	6.09	6.10	22.39	53.1	0.76	52.1	54.0	62.2	1.04	60.8	63.4

Table 1. Tabulated summary of results of LBSPR assessment of data from seven SCS fisheries for SKJ with dome-shaped size selectivity (top) and six fisheries with logistic selectivity.

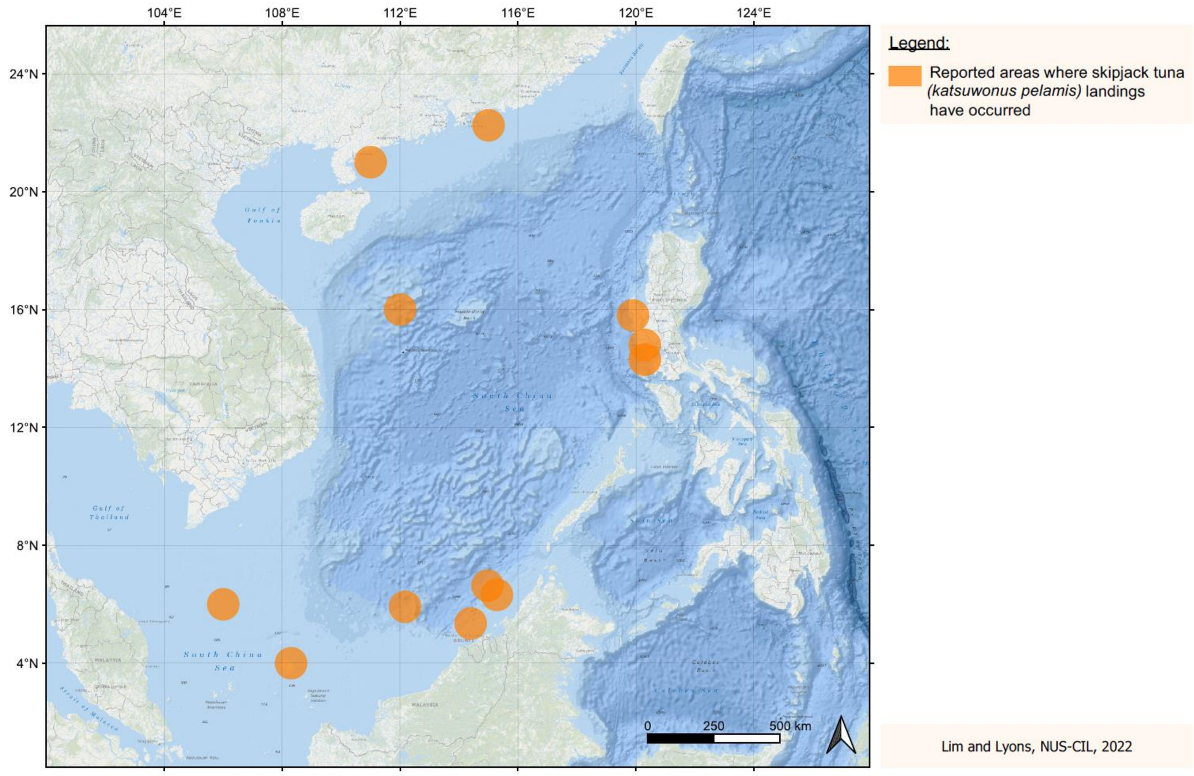

Figure 1. Indicative sampling areas in the SCS for the size catch composition of SKJ analyzed by this study.

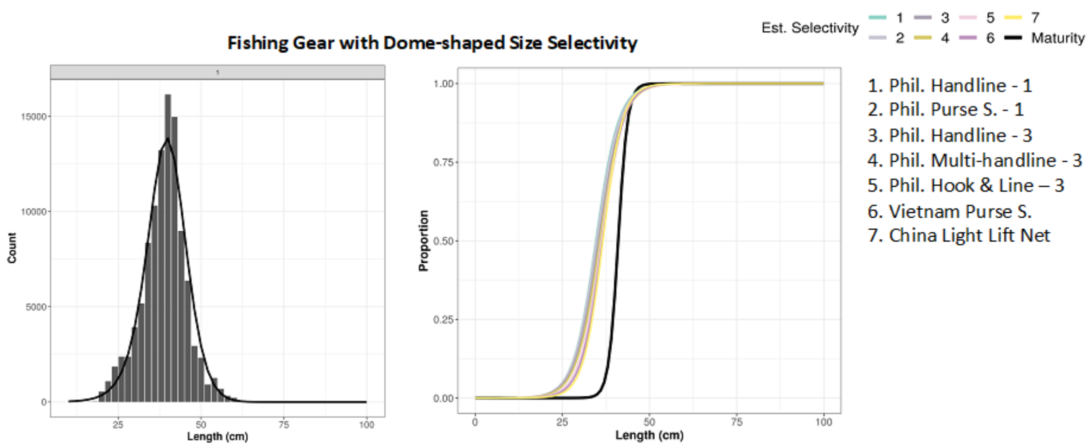

Figure 2. Indicative results from LBSPR assessment of SKJ size composition data from fishing gears with dome-shaped size selectivity. The left-hand panel depicts the size

composition from the Vietnamese purse seine fishery (black bars) and the curve fitted by LBSPR assessment (black curve). The right-hand panel plots the size selectivity curves fitted to the seven data sets (colored curves), relative to the assumed length of maturity curve (black curve). Note the size selectivity are smaller than the size of maturity, so that fish can be caught before becoming adult.

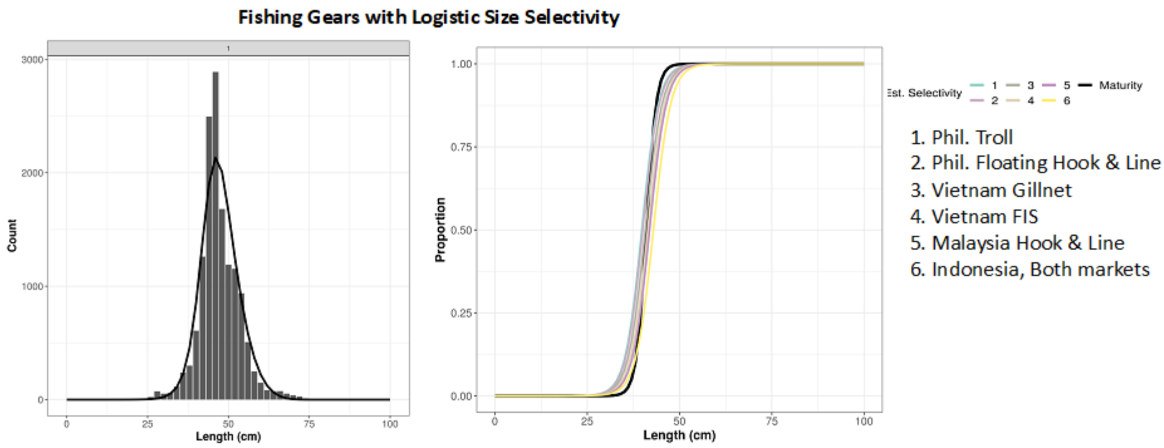

Figure 3. Indicative results from LBSPR assessment of SKJ size composition data from fishing gears with logistic size selectivity. The left-hand panel depicts the size composition from the Vietnamese fishery independent gillnet surveys (black bars) and the curve fitted by LBSPR assessment (black curve). The right-hand panel plots the size selectivity curves fitted to the six data sets (colored curves), relative to the assumed length of maturity curve (black curve). Note the size selectivity are similar to size of maturity, protecting juvenile fishing from being caught.

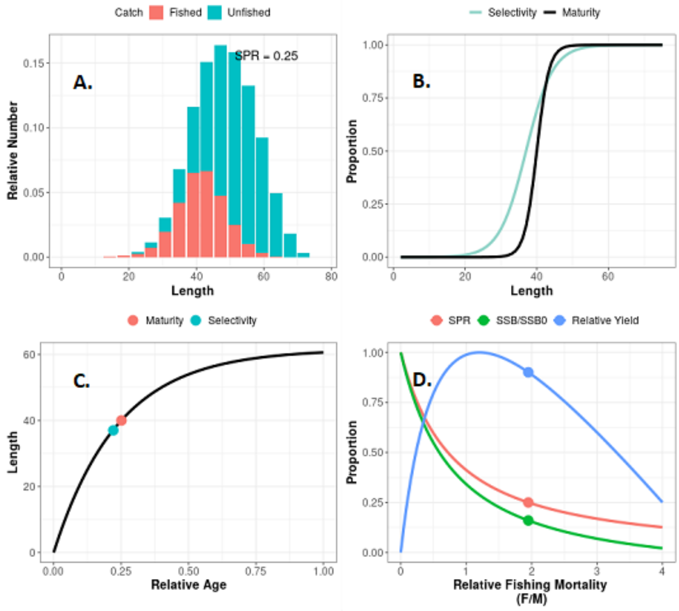

Figure 4. Simulations of the SCS SKJ fishery assuming all catching is done with purse seine fishing. Assumed parameters derived from results from the Vietnamese purse seine fishery (Table 1), stock recruitment steepness h = 7 and SPR = 0.25. (A.) Plot of the simulated size composition of the catch for SPR = 1.0 (grey bars) and SPR = 0.25 (red bars). (B.) Plot of size selectivity curve (grey curve) relative to the size of maturity curve (black curve). (C.) Plot of size selectivity (grey circle) and the size of maturity (red circle) relative to the growth curve (black curve). (C.) As functions of Relative Fishing Pressure (*F/M* – x-axis), plots of potential yield (blue curve), Spawning Potential Ratio (SPR – green curve) and Current Spawning Biomass relative to unfished (red curve).

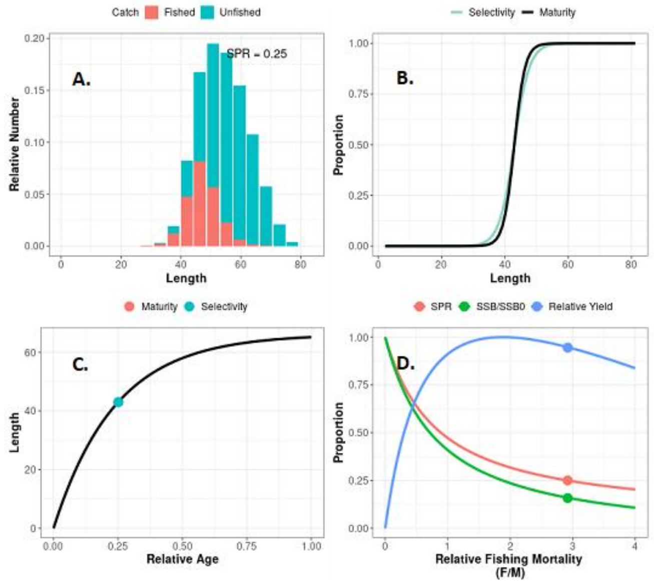

Figure 5. Simulations of the SCS SKJ fishery assuming all catching is done with gillnet fishing. Assumed parameters derived from results from the Vietnamese gillnet fishery (Table 1), stock recruitment steepness h = 7 and SPR = 0.25. (A.) Plot of the simulated size composition of the catch for SPR = 1.0 (grey bars) and SPR = 0.25 (red bars). (B.) Plot of size selectivity curve (grey curve) relative to the size of maturity curve (black curve). (C.) Plot of size selectivity (grey circle) and the size of maturity (red circle) relative to the growth curve (black curve). (C.) As functions of Relative Fishing Pressure (*F/M* – x-axis), plots of potential yield (blue curve), Spawning Potential Ratio (SPR – green curve) and Current Spawning Biomass relative to unfished (red curve).

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