A Common Fisheries Resource Analysis on data-limited Little Tuna stocks in the South China Sea

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Abstract

The 1982 United Nations Convention on the Law of the Sea (UNCLOS) requires coastal states of semi-enclosed seas, like the South China Sea (SCS), to coordinate in the management and conservation of marine environments and living resources, specifically of highly migratory trans-national stocks. Despite being one of the world's top five fishing grounds, sovereignty disputes continue to prevent the formation of any regional fisheries management organisation (RFMO) and bedevil attempting joint fisheries management in the SCS. Aiming to develop new norms and standards for regional cooperation and support parallel domestic fisheries policymaking, scientists from China, Indonesia, Malaysia, the Philippines and Vietnam overcame political constraints and data limitations to develop a Common Fisheries Resource Analysis (CFRA) of Skipjack Tuna (*katsuwonus pelamis*) in 2022 and now, here present an assessment of the SCS Little Tuna (*euthynnus affinis*) resource.

We conclude **that heavy unselective fishing of the nektonic biomass in the north of the SCS by light-falling net fishing has extirpated adult Little Tuna stocks in that region**, and probably the stock of other neritic tunas in that area as well. We recommend the SCS nations re-double their efforts to manage the fisheries under their jurisdictions, but in parallel, to implement agreed trans-national strategies for optimising sustainable production and eco-system resilience. The SCS nations should develop and implement long term plans for phased reductions of fishing capacity, and work together to develop, implement and enforce agreed standard fishing gears and techniques to improve size and species selectivity and make the stocks resilient to growth and recruitment overfishing. The challenge of policy development and implementation should be supported by an international framework for regularising cooperation between government and non-government scientists of coastal states.

Keywords: South China Sea; science diplomacy; RFMO; UNCLOS; data-poor assessment; weight of evidence; neritic pelagics; biomass fishing; larval commons; *euthynnus affinis*

List of Abbreviations

ASEAN	Association of Southeast Asian Nations
CFRA	Common Fisheries Resource Analysis
CPUE	Catch Per Unit Effort
DOF	Department of Fisheries, Malaysia
F/M	Relative fishing pressure
FADs	Fish Aggregating Devices
FAO	Food and Agriculture Organization of the United Nations
FIS	Fishery Independent Surveys
FSWG	Fisheries Science Working Group
HD	Centre for Humanitarian Dialogue
HRI	Human Reproductive Index
IOTC	Indian Ocean Tuna Commission
IUU	Illegal, Unreported, and Unregulated fishing
LBSPR	Length-based Spawning Potential Ratio
LHR	Life History Ratios
LRP	Limit Reference Point
MAE	Ministry of Agriculture and Environment, Vietnam
mtDNA	Mitochondrial DNA
NFRDI	National Fisheries Research and Development Institute, Philippines
RFMO	Regional Fisheries Management Organisation
RIMF	Research Institute for Marine Fisheries, Vietnam
RPOA	Regional Plan of Action
SCS	South China Sea
SCSFRI	South China Sea Fisheries Research Institute, China
SEA	Southeast Asia
SEAFDEC	Southeast Asian Fisheries Development Center
SNPs	Single Nucleotide Polymorphisms
SPR	Spawning Potential Ratio
UNCLOS	1982 United Nations Convention on the Law of the Sea
WCPFC	Western and Central Pacific Fisheries Commission
WoE	Weight of Evidence
WTO	World Trade Organization

1. Introduction

1.1. South China Sea's Fisheries

Simmering contentions about sovereignty over the South China Sea (SCS) have recently risen towards flashpoint. Forming the coastline of multiple countries and territories inhabited by two billion people, the SCS is strategically, economically and ecologically critical to the region and globe (Sumaila and Cheung 2015; Teh et al. 2019). Producing ~12% of wild catches, the SCS is one of the world's top five fishing grounds. Historically it has been characterised by its multitude of small-scale fisheries, many categorised as illegal, unreported or unregulated (IUU) due to their low levels of regulation and documentation. Recent analyses suggest that in aggregate the SCS fisheries exert immense fishing pressure on stocks, having depleted them by 70–95% since the 1950s, and 66–75% over the last 20 years (Chang et al. 2020; Wang et al. 2022). Total production peaked in 2003 and has apparently since declined (Sumaila and Cheung 2015; Teh et al. 2019). Despite its regional and global significance, knowledge of the SCS's fisheries remains sparse, and the severity of the sustainability crises they face has not received the attention deserved, partly because they are so poorly documented (Sumaila et al. 2021).

1.2. The Law of the Sea: Obligations and Political Commitments to Cooperate

The 1982 United Nations Convention on the Law of the Sea (UNCLOS) calls on the coastal states of semi-enclosed seas to coordinate in the management and conservation of living resources and marine environment, specifically calling for cooperation on protecting stocks of highly migratory fish species. In this context, the SCS countries have made numerous commitments to cooperative management. In 2002, the Association of Southeast Asian Nations (ASEAN) and China agreed on a Declaration on the Conduct of Parties in the SCS which states that, "Parties concerned may explore or undertake cooperative activities. These may include … marine environmental protection [and] marine scientific research". In 2017, ASEAN and China declared a Decade of Coastal and Marine Environmental Protection in the SCS which calls for "collective attention and action to protect the marine ecosystem" and emphasises "the need to promote responsible fishing practices." Despite this documentation of good intent, ongoing political disputes have prevented to formation of a regional fisheries management organisation (RFMO) for the SCS, and efforts to collectively assess the status of SCS stocks have been limited.

1.3. The South China Sea Fisheries Science Working Group

In 2018, 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 providing secretariat support to scientists and policymakers from China, Indonesia, Malaysia, the Philippines and Vietnam, aimed at reducing regional tensions. Convening eight times between 2018 and 2022, and benefiting from a wide range of independent expertise, the participating fisheries managers, diplomats, and national security officials – comprising the informal SCS Fisheries Science Working Group (FSWG) – discussed cooperatively managing SCS fisheries resources, and decided to begin building the basis of regional scientific consensus around the status and management of some of key fisheries.

The broad continental shelves of the SCS provide highly productive habitats for an assemblage of oceanic and neritic (coastal) tuna species, all of which are economically important in Southeast Asia, generating export revenues for the countries and providing important protein sources for domestic consumption.

The FSWG agreed to prioritise working on economically valuable transboundary oceanic species using an open and transparent process involving multi-lateral scientific cooperation through a series of Common Fisheries Resource Analyses (CFRA) adhering to agreed principles of:

- Voluntary participation,
- Focusing on issues relevant to policymakers across the region,
- Allowing all participating countries to contribute meaningfully and on an equal footing,
- Avoiding territorial disputes and other political sensitivities, and
- Not requiring the sharing of raw data or other sensitive information.

The FSWG published its first CFRA (Prince et. al, 2023a) focused on Skipjack Tuna (*katsuwonus pelamis*). For the second CFRA, participants prioritised working with Little Tuna (*euthynnus affinis*) an important component of regional fisheries for a multi-species complex of coastal pelagic species. Both species are listed as ''highly migratory" under Annex I of UNCLOS (UN 1982),

1.4. Little Tuna

Little Tuna, also called "Kawakawa" or "Mackerel Tuna", are a relatively short-lived (2-4 years), medium-sized (2-5kg) neritic or coastal, tuna species broadly distributed through the tropical and subtropical coastal waters of the Indo-Pacific region (Froese and Pauly, 2007; Rohit et al. 2012). Although listed as a ''highly migratory species'' in UNCLOS (UN 1982), along with the larger bodied oceanic tunas, Kawakawa are rarely captured beyond the edge of the continental shelf (Chiou & Lee 2004). Rather than being specifically targeted for catching, Kawakawa are commonly caught 'incidentally'; one of the more abundant species, in an assemblage of medium to large bodied neritic pelagic species that includes longtail (*thunnus tonggol*), frigate (*auxis thazard*) and bullet (*a. rochei*) tunas, as well as seerfishes (*scomberomorous* spp.).

This assemblage of neritic pelagics supports significant commercial and artisanal fisheries in many of the countries bordering the central, southwestern, and western Pacific Ocean, and the eastern and western Indian Ocean (Williamson 1970; Chiou et al. 2004). A diverse range of traditional small-scale commercial and artisanal fishing fleets catch the assemblage using techniques that encompasses hand-, drop-, and long-lining, as well as trolling, drifted gillnets, stationary coastal traps and purse seining (Yesaki 1994; Siriraksophon, 2017; Saleh et al. 2021). From 1980-2000 some 32 countries reported combined landings of >150 000 $t.yr^{-1}$ (FAO, 2003) and global production increased steadily from <170,000 t in 2009 to >200,000 t by 2011; although this trend may also reflect improved reporting standards (Ahmeda et al. 2015). On the Indian Ocean side of the Malaysian Peninsular and Indonesian Archipelago (FAO Area 61) Kawakawa is the fourth most important tuna by recorded tonnage, and through the Western and Central Pacific Ocean (FAO Area 71) the fifth most important (Griffiths et al. 2019).

A significant development over the last two decades has been the development and expansion of 'light-falling net' fishing (Wu et. al 2016) which instead of targeting sub-adult and adult fish, catches the larvae, juveniles and sub-adult of neritic species, as a by-product of fishing for purple-back flying squid (*sthenoteuthis oualaniensi*).

1.5. Data-Limited Fisheries Assessment

By comparison to the larger bodied oceanic tunas, little priority has been placed on research into any of the smaller-bodied lower-value neritic tunas. Consequently, there has been almost no fundamental research into the fisheries biology, stock structure or movement of Kawakawa. Even long term catch trends are uncertain, as until relatively recently catches of neritic tuna have been lumped together for reporting purposes, so that trends in regional catches remain uncertain until recent decades (IOTC 2012).

Almost by definition fisheries the assessment of neritic tuna stocks is limited by the availability of data, meaning there is insufficient catch data and biological information to support standard age-based biomass assessment (Hilborn & Walters 1992; Prince & Hordyk 2018). Being 'data-limited' makes it necessary to apply simpler, and necessarily cruder, methods to evaluate whatever information exists, or can be easily collected (Harford et al. 2022). Here we report on how the CFRA overcame the challenge of being 'data-limited' to develop a regional assessment of the SCS Kawakawa stocks.

1.6 Little Tuna fisheries around the South China Sea

The Southeast Asian Fisheries Development Centre (SEAFDEC) compiles annual catch estimates for the UN's Food and Agriculture Organisation (FAO) statistical Areas 61 and 71 of the Western and Central Pacific Fisheries Commission (WCPFC), aggregating statistics across an area that includes, but extends far beyond, the SCS (Griffiths et al. 2019). The two countries consistently reporting the largest catches are Malaysia (>50,000 $t.yr^{-1}$) and Thailand (>45,000 $t.yr^{-1}$). Saleh et al. (2021): According to the Annual Fisheries Statistics of Malaysia in 2016, about 32 % of the total landing of neritic tunas (73,903 MT) was contributed by Kawakawa.

As stocks of the more valuable larger bodied oceanic tunas have become fully exploited and catches have plateaued or declined, tuna processing companies have increasingly turned to the neritic tuna species for growth, which initially resulted in the steady escalation of landings and fishing pressure (Siriraksophon, 2017; Griffiths et al. 2019). An FAO review of the state of the world marine fishery resources (FAO 2011) raised concerns over the increasing exploitation of neritic tunas (Majkowski et al. 2011), which in 2015 this in a Regional Plan of Action for Sustainable Utilization of Neritic Tunas (RPOA Neritic Tunas) for the SCS (2017). Subsequent risk assessments of neritic tuna stocks conducted for SEAFDEC concluded that the regional Kawakawa stocks on both the Pacific and the Indian Ocean sides of SE Asia should be considered fully exploited, but in the safe zone (green), and not approaching the states of overfishing or overfished (Nishida et al. 2017; Saleh et al. 2021).

1.7 Stock structure and movement

The actual stock structure of Kawakawa stocks through the Southeast Asian region is unclear and the various opinions are conjecture at best (Devaraj & Vivekanandan 1997). A preliminary studying of the genetic variation cross Southeast Asia (SEA) by Santos et al. (2010), observed generally similar levels of genetic heterogeneity across the SEA region, which they interpreted as evidence for pan-mictic (freely mixing) populations. Similarly, a genetic study of long-tail tuna by Willette et al. (2016) observed similar levels of heterogeneity across the region, and concluded two stocks exist in SEA waters; one on the Pacific Ocean, and another on the Indian Ocean side, aligning nicely with the FAO fishing areas 57 and 71, respectively (Figure 1). This assumed two-stock structure has since been used for SEAFDEC assessments, which aggregate catch trends separately for the Indian Ocean and Pacific sides of the Malaysia peninsula.

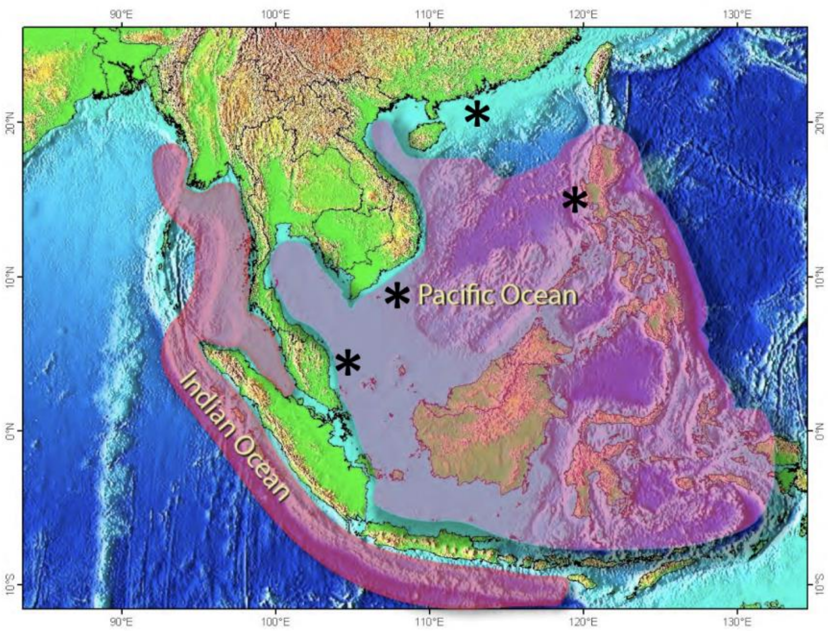


Figure 1. An illustration of the two-stock hypothesis assumed for the purpose of SEADEC's assessment of neritic tuna in Southeast Asian waters, showing the distribution of an Indian Ocean and Pacific Ocean stock, each of which are assumed to be freely mixing

(panmictic) within the respective stock. Black asterisks indicate the approximate sampling locations used in this study.

However, both Santos et al. (2010) and Willette et al. (2016) acknowledged that there are limitations in their sample size as well as in the maternally-inherited mitochondrial DNA (mtDNA) D-Loop marker they used. Hence, they pointed out there might be finer population structures in SEA if sampling size and locations are increased as well as more robust genetic markers such as nuclear DNA markers or single nucleotide polymorphisms (SNPs) are employed. In addition, the sampling methodologies of many early genetic studies of marine species, may have been dispersed too sparsely and patchily to successfully test their starting hypotheses (see Temby et al. 2007). The conclusions advanced by Santos et al. (2010) and Willette et al. (2016) probably only indicate the scale at which genetic mixing occurs over generations, rather than the scale at which primarily self-recruiting populations need to be managed. Originally, Yesaki (1979) inferred that Kawakawa must have an intra-regional stock structure because of the intra-regional differences in size of maturity and the timing of spawning and recruitment. For example; two recruitment pulses per year through northern Thailand and the Philippines, a single seasonal pulse in Hong Kong, and year-round spawning off the Pacific coast of the Philippines (Wade 1950). Santos et al. (2010) concluded that the evidence provided by Yesaki (1979) taken together with their own observations suggesting intra-regional stock structure, provided the impetus to look for further evidence of population structure, because the implication was that Southeast Asia would require sub-regional management.

With each new application of cutting-edge research techniques to scombrids, new evidence seems to be produced for a greater degree of philopatry (faithfulness, or homing to, specific areas) than previously expected (Prince et al. 2023a), even amongst the poorly studied neritic species; leading to assumptions about the scale of component management units being revised downwards. Jackson et al. (2014) observed regional genetic subdivision in Kawakawa, consistent with the barriers to larval dispersal found near Sumatra, Sulawesi, and Papua, which suggested that the Halmahera and Mindanao eddies, as well as the Indonesian flowthrough, were oceanographic forces that maintained genetic divergence between demes of pelagic fishes. Like Santos et al. (2010) before them, Jackson et al. (2014) suggested re-evaluating the scale of coastal pelagic stocks, as did Griffiths et al. (2019) who conducted a similar study of long tail tuna.

In this context it seems unlikely that Kawakawa stocks are mixing freely across the entire SEA region on the Pacific side of the Malaysian peninsula, although over longer multi-generational time frames genetic flows of this scale must occur. We assume that the Kawakawa fisheries in the SCS are likely to be fishing multiple relatively independent, local stocks distributed along the region's shelf breaks and around islands, with sufficient interactions over longer time-frames for some genetic mixing, but insufficient to maintain genetic homogeneity, or potentially, to prevent concentrated fishing pressure, depleting component areas of stock. We assume that the 'two regional stocks' previously assessed (Nishida et al. 2017) are effectively meta-populations; networks of loosely connected local populations (Figure 2), with gene flow being maintained by a small degree of long-distance larval dispersal through an overlapping larval pool, or larval commons, as well as the occasional distant movement of individuals (Moore et al. 2020).

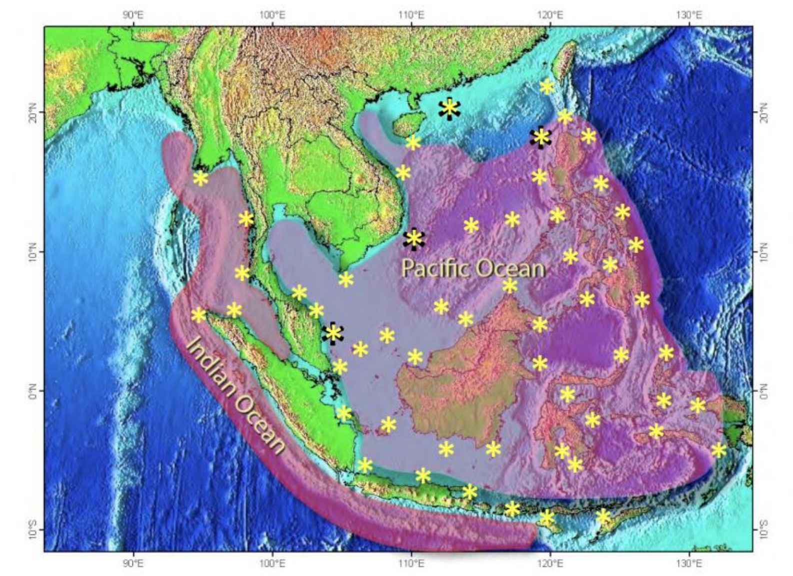


Figure 2: An illustration of an alternative form of stock structure assumed for this study in which the two broad stocks are assumed to be meta-populations, comprised of multiple spawning aggregations (indicated by asterisks) off many capes, points, along coastlines and around islands, each supporting local populations which are primarily self-recruiting; but with sufficient overlap to create a 'larval commons' through which genetic exchange is maintained across the entire meta-population over generational time frames.

1.8 The Little Tuna stock off Hong Kong

An early high-quality study of Kawakawa completed in 1967-69 around Hong Kong by Williamson (1970) with the aim of developing a local purse seine fishery, documented Little Tuna stocks along the south coast of Guangdong, China. Williamson (1970) describes how at that time, the adults spent most of the year dispersed out across the continental shelf preying on schooling pelagic fish and cephalopods, and only aggregated along the coast during May-August to spawn. Williamson observed the catch during the spawning season to be primarily comprised of two cohorts (Figure 3); a larger main cohort of entirely ripe 2+ adults (mean length = 50-70cm with mean weight = 4.5kg), and a lesser mode of smaller 1+ fish (mean length 40- 50cm with mean weight = 1.9kg), of which about 10% were immature non-spawning fish. Outside the spawning season, Williamson caught smaller quantities of Kawakawa with a broader range of sizes (24-70cm), but primarily sub-adult fish (24-45cm).

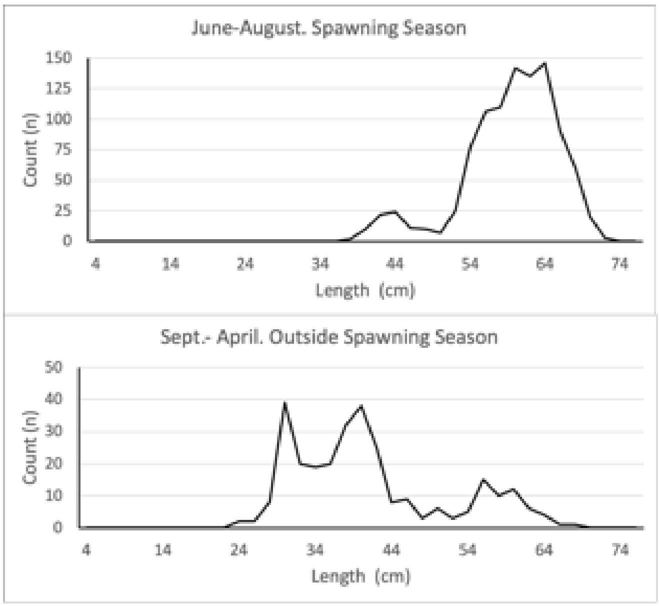


Figure 3. Re-digitised from Williamson (1970), length frequency histograms for Kawakawa caught in the vicinity of Hong Kong during 1967-69.

2. Methods

The broad aim of the CFRA has been to develop a composite regional assessment of the SCS Kawakawa resource through the parallel use of a standard methodology to enable comparable, but independent, national analyses of existing, or easily collected data. In that context, the original CFRA began by surveying the available data sets in each country before concluding that catch size composition was the only universally available form of data, or the form that could be feasibly collected during the project's life-span. After a review of several methodologies by international experts, the length-based assessment of spawning potential ratio (LBSPR) (Hordyk et al. 2015a,b) was selected as being the most feasible, simplest, and informative.

2.1. Length-based Spawning Potential Ratio assessment

Developed specifically for fisheries for which only catch size composition data can be collected, the LBSPR technique estimates the spawning potential ratio (*SPR*) of populations, which measures the risk of recruitment failure (Goodyear 1993). Developed during the 1970s, originally for application to North Atlantic fisheries, *SPR* is defined as the proportion of a stock's natural, or unfished, reproductive potential, allowed by fishing (Goodyear 1993). When unexploited, fish live out natural life-spans and fulfilling their natural reproductive potential, or spawning (ie. *SPR* = 1.0). Fishing reduces average life-spans and the proportion of the 'natural' spawning that can be fulfilled (*SPR* < 1.0). The LBSPR algorithms compares catch size compositions to the length at which sexual maturity is attained (L_m), and potential average maximum size (L_∞), to estimate *SPR* and relative fishing pressure (*F/M*: where *F* is 'fishing mortality', and *M* is 'natural mortality').

The *SPR* metric is conceptually similar to the Human Reproductive Index (*HRI*) which is the average number of children per couple that survive to adulthood. With *HRI* = 2.1 being the 'Replacement Level' required for human couples to replace themselves and stabilize populations, above that level populations grow and below they decline. Internationally in fisheries *SPR* = 0.2 is regarded as the 'replacement level' and used generically as a Limit Reference Point (LRP) which stocks should be prevented declining below (Mace and Sissenwine 1993). While *SPR* = 0.3 – 0.4 is accepted as a target range for maximizing sustainable yields, and *SPR* = ~ 0.5 the target for optimising economic returns (Table 1).

For this analysis the LBSPR algorithms used were accessed through the website: http://barefootecologist.com.au.

Table 1. Generic reference points for fisheries management based on Mace and Sissenwine (1994).

Reference Point for Management	**Value of Spawning Potential Ratio**

Limit – Replacement Level	0.20
Lower Target Maximum Sustainable Yield	0.30
Higher Target Maximum Sustainable Yield	0.40
Maximum Economic Yield	0.50
Target for Stock Rebuilding	0.60

2.1.1. Data Requirements

The data required for the LBSPR methodology are:

1. Catch size composition data that are indicative adult portion of stocks. If the type of fishing sampled fails to catch the largest size classes, the resulting estimates of *SPR* will be biased low, and *F/M* biased high.
2. Estimates of L_m defined by L_{50} and L_{95}, the sizes at which 50% and 95% of a population mature into adults.

The LBSPR methodology is based on the simplifying assumption that assessed populations exist in a relatively stable ‘equilibrium’ state, so that size compositions are expected to change relatively slowly, over the life-span of species. In this context it is valid to analyse data aggregated over several years.

2.1.2. Life History Ratios

As applied here, the LBSPR methodology requires assumptions about two life history ratios (*LHR*) that define the shape of adult size compositions relative to L_{50} (Hordyk et al. 2015a):

a. L_{50}/L_∞ - the size at which fish mature relative to the average maximum size (L_∞) they would attain of they survived to an infinite age; and
b. M/K - the rate at which a cohort of fish dies off from natural causes (M), divided by the von Bertalanffy growth parameter (K), which is the instantaneous annual rate of growth towards L_∞.

The *LHR* remain similar across species’ ranges, genera and families (Holt 1958) and are best estimated generically from aggregations of high-quality age and growth studies (Prince et al. 2023b). Estimates have been derived through meta-analysis (Prince et al. 2023b) for Scombridae (M/K = 0.99; n = 90, SD = 0.46 and L_m/L_∞ = 0.65; n = 39, SD = 0.14).

Together these studies suggest a plausible range of LHR estimates which we applied as 12 combinations of input assumptions (M/K = 1.0, 1.05, 1.10, 1.15 and L_{50}/L_{∞} = 0.60, 0.65, 0.70) which we applied to each dataset.

2.1.3. Size of Maturity

Kawakawa mature during their second year of their life (35-45cm) to spawn serial batches of eggs over several extended spawning seasons (Rohit et al. 2012). Previously published studies, synthesised in Table 2, indicate the size at maturity is highly variable between locations, ranging from 37-60 cm. The CFRA could not agree on any single defensible estimate to be used with all datasets, with each country preferring different estimates based on local studies both published and unpublished, most of which we considerably smaller than suggested in Table 2.

With the aim of applying a standard methodology in parallel to the national datasets we analysed all datasets assuming a range of size of maturity estimates; L_{50} = 20, 25, 30, 35, 40cm, 45cm, which together with the 12 combinations of LHR assumptions resulted in 60 SPR estimates being derived with each national data set.

Table 2. A synthesis of published studies of size of maturity in Kawakawa illustrating the geographic variability that typifies the species.

Location	L50 (cm)	Measurement	Sex	Reference
Taiwan	48	FL	All	Chiou, W-D., Cheng, L-Z., Chen, K-W. 2004. Reproduction and food habits of Kawakawa *Euthynnus affinis* in Taiwan. J Fish. Soc. Taiwan 31: 23-38.
Hong Kong	40-50	FL	All	Williamson, G.R. (1970). Little Tuna *Euthynnus affinis* in the Hong Kong area. Bulletin of the Japanese Society of Scientific Fisheries Vol. 36: 9-18.
South China Sea	37-42	FL	All	Klinmuang (1978) in Deepti et al. (2012)
Philippines Pacific Coast	44.5	FL	F	Wade, C. B. 1950. Observations on the spawning of Philippine tuna. Fish. Bull. U. S. S. Fish. Wild. Serv., 51: 409-423.
Philippines Pacific Coast	43.1	FL	M	Wade, C. B. 1950. Observations on the spawning of Philippine tuna. Fish. Bull. U. S. S. Fish. Wild. Serv., 51: 409-423.
Philippines	49	FL	All	Bunag, D.M. (1956). Spawning habits of some Philippine tuna based on diameter measurements of the ovarian ova. J. Philipp. Fish. 4: 145-177.
Philippines	38.5	FL	All	Ronquillo (1963) in Deepti et al. (2012)
Malaysia	42.6	FL	M	Saleh, M.F., Jamon, S., Jaafar, K., Fatah, N.N.A, Muda, O., Azmi, M.S., (2021). Biological Aspect and Population Parameters of Kawakawa (*Euthynnus affinis*) in Tok Bali Fish Landing Ports, Kelantan, Malaysia. Malaysian Fisheries Journal 20: 26-49.
Malaysia	39.3	FL	F	Saleh, M.F., Jamon, S., Jaafar, K., Fatah, N.N.A, Muda, O., Azmi, M.S., (2021). Biological Aspect and Population Parameters of Kawakawa (*Euthynnus affinis*) in Tok Bali Fish Landing Ports, Kelantan, Malaysia. Malaysian Fisheries Journal 20: 26-49.
Gulf of Thailand	40	FL	All	Cheunpan (1984) in Deepti et al. (2012)
Bali, Indonesia	45.3	FL	All	G L Arnenda, F Rochman, A Wujdi, R Kurniawan, N I Wiratmini and I M S Wijana (2021) Reproductive biology of male *Euthynnus affinis* (Cantor, 1849) in Kedonganan Bali IOP Conf. Series: Earth and Environmental Science 860
Indo Pacific	38	FL	All	Yesaki (1979) in Deepti et al. (2012)
Papua New Guinea	48.9	FL	All	Wilson (1981) in Yesaki (1979) and Deepti et al. (2012)
Gulf of Aqaba	46	FL	All	Al-Zibdal, M., Odan, N. (2007) Some findings related to the fishery status, growth, reproductive biology and feeding habitat of two Scombrid fish from Gulf of Aqaba, Red Sea.
India - NW Coast	48	FL	All	Mudumala, V.K., Ma Farejiya, M.K., Mali, K.S., Siva, A., RajaSanadi, R.B., PradnSawant, P.A., and Tailor, R.K. (2018). Reproductive biology of three neritic tunas (family: scombridae) inhabiting the north-western coastal waters of India. IJCRT 6: 1705347 707- 718
India - Vizhinjam	48	FL	All	Rao (1964) in Deepti et al. (2012)
India - Tuticorin	44	FL	M	Jude et al. (2002) in Deepti et al. (2012)
India - Tuticorin	43	FL	F	Jude et al. (2002) in Deepti et al. (2012)
India - Mangalore	44	FL	M	Muthiah (1986) in Deepti et al. (2012)
India - Mangalore	43	FL	F	Muthiah (1986) in Deepti et al. (2012)
Indian Seas	43-44	FL		James et al. (1992) in Deepti et al. (2012)
India - N. Bay Bengal	38.5	FL	F	Deepti V.A. Iswarya and Sujatha K.2012. Fishery and some aspects of reproductive biology of two coastal species of tuna, *Auxis thazard* (Lacepede, 1800) and *Euthynnus affinis* (Cantor, 1849) off North Andhra Pradesh, India. Indian Journal of Fisheries 59(4):67-76
India - N. Bay Bengal	36.7	FL	M	Deepti V.A. Iswarya and Sujatha K.2012. Fishery and some aspects of reproductive biology of two coastal species of tuna, *Auxis thazard* (Lacepede, 1800) and *Euthynnus affinis* (Cantor, 1849) off North Andhra Pradesh, India. Indian Journal of Fisheries 59(4):67-76
All - Indian waters	37.7	FL	All	Rohit, P. Chellappan, A. Abdusssamad, E. M.et al. . 2012. Fishery and bionomics of the little tuna, *Euthynnus affinis* (Cantor, 1849) exploited from Indian waters, Indian J. Fish., 59(3): 33-42.

2.2. Weight of Evidence Evaluation of Data-poor Fisheries

The LBSPR methodology is a simplified form of assessment that, subject to a range of assumptions, can enable relatively crude snapshots of stock status. Prevented by data-limitations from applying more sophisticated forms of analysis, and cognisant of the limitations of LBSPR assessment, we applied it within a weight of evidence (WoE) approach which involves three steps: (1) assembling differing lines, or types, of evidence, which in this case includes both the context and analyses of catch size composition, (2) weighing all the evidence, and (3) integrating the evidence into a holistic interpretation (Hardy et al. 2017).

Participants in each country were advised on the application of the LBSPR methodology to their own data, and only during the final stages of the assessment process, shared the results of their analyses with other countries to forge a consensus on the overall status of the Kawakawa stocks in the SCS. Although previous assessments have assumed and estimated region-wide trends for the SCS (Nishida et al. 2017; Saleh et al. 2021), our approach has been to use each countries' data to indicate stock status in their region of the SCS, and in this way enable our data to reveal, whether broad uniform trends are in fact occurring, as previously assumed, or whether disparate regional trends consistent with a more complex stock structure than previously assumed, requires a more 'pixilated' assessment approach. Our preliminary analyses having indicated disparate regional trends, we concluded that attempts to model uniform stock dynamics across the region would obscure the true nature of the situation.

3. Results

3.1 Vietnam

Kawakawa is harvested in Vietnam primarily as a secondary or incidental caught species in both the purse seine fishery, which primarily targets small pelagic fish, and also the drift gillnet fisheries which targets Skipjack Tuna and the neritic tuna assemblage. The fishing grounds extend along the coast of Vietnam, ranging from the northern region (the mouth of the Tonkin Gulf) to the southern waters off Con Son Island. Fishing occurs year-round with peak catches during the months of northeast monsoon: October to March.

In Vietnam, the Research Institute for Marine Fisheries (RIMF) of the Ministry of Agriculture and Environment provided access to data from the Fishery Independent Surveys (FIS) of fish stocks that have been conducted regularly across the fishing grounds (Vinh et al. 2001, Raakjaer et al. 2007). The FIS is conducted in October and April, in line with the northeast monsoon season (October to March) and the southwest monsoon season (April to September), according to a scientific protocol involving drift gillnets being set at 60 fixed stations across the fishing grounds. A range of stretched mesh sizes are used with the aim of ensuring logistic size-selectivity so that all adult size classes are equally vulnerable to capture. We analysed data from the surveys conducted during 2011, 2012, 2015, and 2018.

Kawakawa were sampled from 8-15 of the 60 sites sampled each year, mostly off southern Vietnam 5-10ºN; 106-110ºE (Figure 1). The 323 fish sampled ranged in fork length from 20-55cm (Figure 4) were almost entirely adult or sub-adult. Only 5 juvenile fish were observed. Based on sample we could estimate L_{50} = 33.3 cm and L_{95} = 38.0 cm (Unpublished data; Vu Viet Ha, RIMF, MAE).

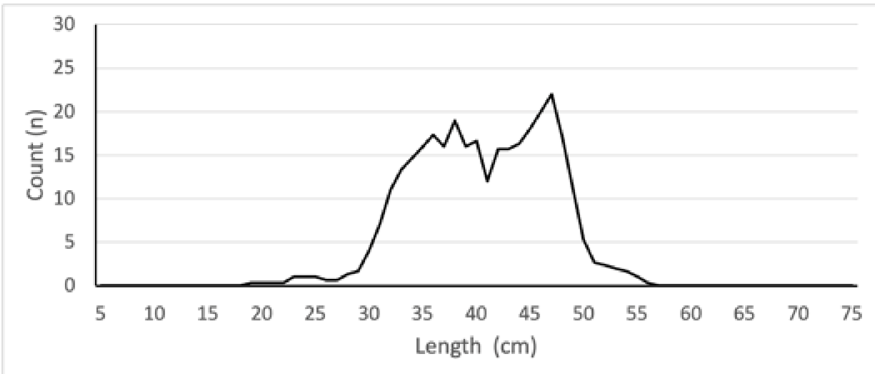


Figure 4. Size composition of Kawakawa taken during independent Vietnamese fishery surveys, 2011-2018.

A mean SPR = 0.61 (SD = 0.42) was estimated across all scenarios (Table 3). With $L_{50} \leq$ 30cm SPR estimates were implausibly high (SPR = 1.0) given the on-going Vietnamese fishery. With L_{50} =35-45cm plausibly lower estimates of SPR resulted (0.03-0.52).

Table 3. Estimates of mean SPR derived with the length-frequency data for Kawakawa caught during Vietnamese fishery independent surveys 2011-2018.

Mean of SPR		**Assumed M/K**			
L50 (cm)	**1**	**1.05**	**1.1**	**1.15**	**Grand Total**
20	1.00	1.00	1.00	1.00	**1.00**
25	1.00	1.00	1.00	1.00	**1.00**
30	1.00	1.00	1.00	1.00	**1.00**
35	0.44	0.46	0.49	0.52	**0.48**
40	0.13	0.13	0.14	0.19	**0.15**
45	0.03	0.04	0.04	0.04	0.04
Grand Total	**0.60**	**0.61**	**0.61**	**0.62**	**0.61**

3.2. Philippines

The Philippines' National Fisheries Research and Development Institute (NFRDI), under the Department of Agriculture, provided data collected through the National Stock Assessment Program 2015-2022 in two regions ; region 1, off the north-western corner of the Philippines extending from Bangui Bay (18.6ºN; 120.7ºE), to Dasol Bay (15.9ºN; 119.8ºE) and out to Scarborough Shoal (15.1ºN; 117.5ºE); and Region 3, the Zambales Coast (14.8ºN; 120.3ºE), the adjacent west coast to the south of Region 1, closest to Manila (Figure 1). The monitored landings of Kawakawa are relatively small in both regions (<50t). Kawakawa are reported as being caught by a wide range of methods, each of which catches a specific size range of fish (Figure 5).

Pons et al. (2019) have shown that the LBSPR method produces the most accurate estimates when data from catches that most effectively sample the adult part of the stock. As the FSWG members from the Philippines estimate the size of maturity as L_{50} = 23cm and L_{95}= 35cm which the manually baited coastal longlines, with either smaller or bigger hooks – that is multi-handline and multi-hook & line respectively – catch primarily juveniles and sub-adults. Bottom set gillnet and purse seine primarily land sub-adults, while trolling and the small-scale artisanal hand-line fishery (3-5 fishers using hand-lines from small day fishing vessels) land the greatest proportion and size range of adult fish.

From Region 1 we analysed length data from handlines and trolling, expecting those catches to most accurately represent the adult size composition in that area. From Region 3 we analysed length data from handlines and purse seine, expecting the most accurate estimates of SPR from the handline method assumed to most accurately represent the adult size composition in that area and estimates from the purse seine catch to be bound our estimates by being biased low.

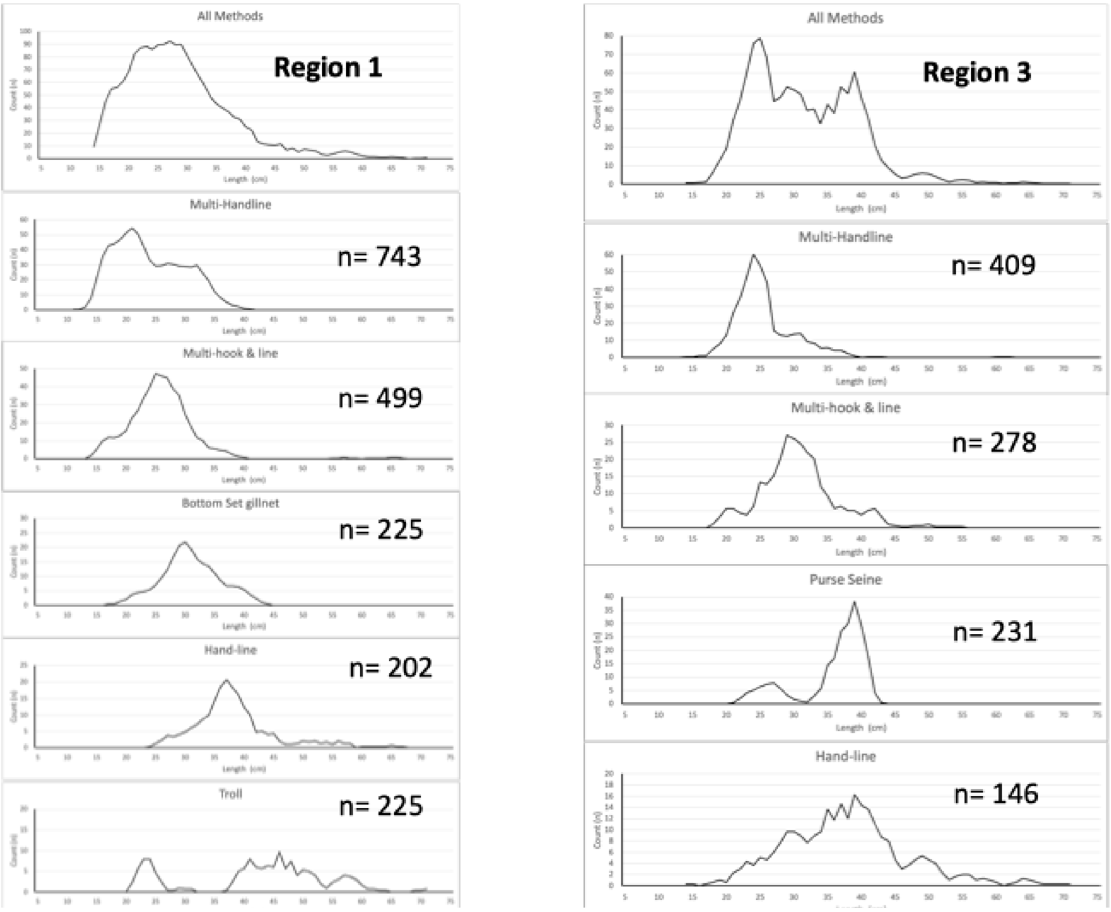


Figure 5. Length frequency histograms by gear type for catches of Kawakawa sampled in Regions 1 and 3 of the Philippines.

3.2.1 Region 1 Handline

Using Region 1 handline catches we estimated an average SPR = 0.51 (SD=0.41) was estimated across all scenarios (Table 4). Plausible estimates of mean SPR (0.12-0.80) were derived assuming L_{50} = 30-40cm. Implausibly high estimates of mean SPR (1.0) resulted from assuming L_{50} = 20-25cm, and implausibly low estimates of mean SPR (>0.05) resulted from assuming L_{50} = 45cm.

Table 4. Estimates of mean SPR derived with the length-frequency data for Kawakawa caught in Philippines Region 1 using handlines.

Mean of SPR	**M/K**	**M/K**	**M/K**	**M/K**	
Size of Maturity	**1**	**1.05**	**1.1**	**1.15**	**Grand Total**
20	1.00	1.00	1.00	1.00	**1.00**
25	1.00	1.00	1.00	1.00	**1.00**
30	0.71	0.74	0.77	0.80	**0.76**
35	0.31	0.32	0.35	0.37	**0.34**
40	0.12	0.12	0.13	0.14	**0.13**
45	0.03	0.03	0.04	0.04	**0.04**
Grand Total	**0.53**	**0.54**	**0.55**	**0.56**	**0.54**

3.2.2 Region 1 Trolling

Using Region 1 troll catches we estimated an average SPR = 0.81 (SD=0.29) was estimated across all scenarios (Table 5). Plausible estimates of mean SPR (0.25-0.70) were derived only assuming L_{50} = 40-45cm. The large size of fish in these samples produced implausibly high estimates of mean SPR (~1.0) with lower assumed sizes of maturity.

Table 5. Estimates of mean SPR derived with the length-frequency data for Kawakawa caught in Philippines Region 1 by trolling.

Mean of SPR	**M/K**	**M/K**	**M/K**	**M/K**	
Size of Maturity	**1**	**1.05**	**1.1**	**1.15**	**Grand Total**
20	1.00	1.00	1.00	1.00	**1.00**
25	1.00	1.00	1.00	1.00	**1.00**
30	1.00	1.00	1.00	1.00	**1.00**
35	0.92	0.94	0.95	0.97	**0.95**
40	0.59	0.63	0.67	0.70	**0.65**
45	0.25	0.27	0.29	0.31	**0.28**
Grand Total	**0.79**	**0.81**	**0.82**	**0.83**	**0.81**

3.2.3 Region 3 Handline

Using the length data from the Region 3 handline fishery (Figure 5) we estimated an average of SPR = 0.66 (SD=0.39) across all scenarios. Scenarios assuming L_{50} < 30cm resulted in implausibly high SPR estimates (1.0) given the magnitude of on-going catches (Table 6) but with $L_{50} \geq 35$cm plausible estimates of average SPR (0.08-0.71) resulted.

Table 6. Estimates of mean SPR derived with the length-frequency data for Kawakawa caught in Philippines Region 3 by with handlines.

Mean of SPR	**Assumed M/K**				
L50 (mm)	**1**	**1.05**	**1.1**	**1.15**	Grand Total
20	1.00	1.00	1.00	1.00	1.00
25	1.00	1.00	1.00	1.00	1.00
30	0.95	0.98	1.00	1.00	0.98
35	0.59	0.64	0.68	0.71	0.66
40	0.22	0.24	0.26	0.28	0.25
45	0.08	0.09	0.09	0.10	0.09
Grand Total	**0.64**	**0.66**	**0.67**	**0.68**	**0.66**

3.2.4 Region 3 Purse Seine

Using the purse seine catch data (Figure 5) resulted in an average estimate of SPR = 0.40 (SD=0.40) across all scenarios (Table 7). Scenarios assuming L_{50} = 25cm and 45cm resulted in SPR estimates that were respectively, implausibly high (1.0) or low (0.0), given we know the stock has been fished for several decades; but with L_{50}s in the range 25-40 cm the average estimates of SPR (0.86-0.02) were plausible (Table 7).

Table 7. Estimates of mean SPR derived with the length-frequency data for Kawakawa caught in Philippines Region 3 by with handlines.

Mean of SPR			**Assumed M/K**		
L50 (mm)	**1**	**1.05**	**1.1**	**1.15**	Grand Total
20	1.00	1.00	1.00	1.00	1.00
25	0.83	0.85	0.84	0.86	0.85
30	0.38	0.40	0.41	0.43	0.41
35	0.12	0.12	0.13	0.14	0.13
40	0.02	0.02	0.03	0.03	0.03
45	0.00	0.00	0.00	0.00	0.00
Grand Total	**0.39**	**0.40**	**0.40**	**0.41**	**0.40**

3.3. Malaysia

The Annual Fisheries Statistics of Malaysia in 2016 record ~32 % of the total landing of neritic tunas (73,903 MT) being comprised of Kawakawa (24,284 MT), of which ~63% is landed from the east coast of Peninsular Malaysia (Saleh et al. 2021). Kawakawa is caught mainly with purse seine either by targeting Fish Aggregating Devices (FADs) or free-swimming schools. It is caught along with other species by fishers either targeting small neritic pelagics with small mesh nets (1"), or targeting Skipjack Tuna with a larger 3" mesh.

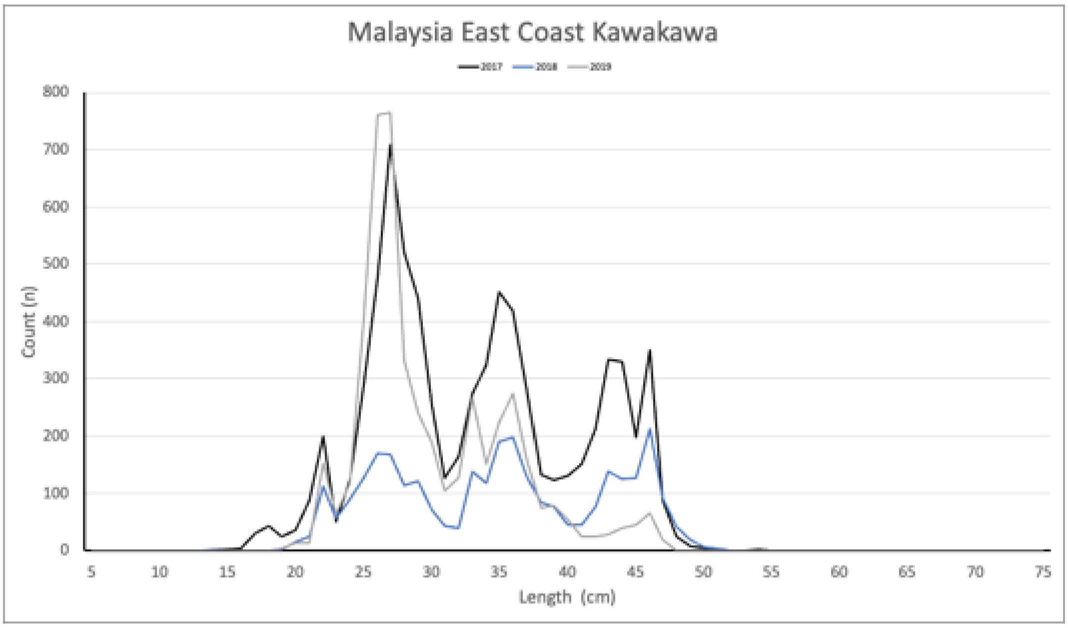


Figure 6. Length-frequency histogram for Malaysian catches of Kawakawa in Malaysia's East Coast.

The size composition of Kawakawa was sampled by the Malaysian Department of Fisheries (DOF) through their routine monitoring of the tuna catch landed into Tok Bali, Kelantan during 2017-2019. The length-frequency histogram for the Malaysian catches reveals three distinct modal size groups (Figure 6). The CFRA members from Malaysia working with the CFRA favour using the size of maturity estimate L_{50} = 33cm and L_{95}= 35cm, which, suggesting the three size classes are comprised respectively of juveniles, sub-adults and adults.

Table 8. Estimates of mean SPR derived with the length-frequency data for Kawakawa landed onto the Malaysian east coast 2017-2019.

Average of SPR		M/K			
L50	**1**	**1.05**	**1.1**	**1.15**	**Grand Total**
20	1.00	1.00	1.00	1.00	**1.00**
25	1.00	1.00	1.00	1.00	**1.00**
30	0.59	0.64	0.66	0.68	**0.64**
35	0.18	0.20	0.15	0.23	**0.19**
40	0.06	0.07	0.08	0.08	**0.07**
45	0.02	0.02	0.03	0.03	**0.03**
Grand Total	**0.48**	**0.49**	**0.49**	**0.51**	**0.49**

An average SPR = 0.49 (SD=0.43) was estimated across all scenarios (Table 8). Plausible estimates of mean SPR (0.06 – 0.68) were derived assuming L_{50} =30-40cm. With $L_{50} \leq$ 25cm SPR estimates were implausibly high (SPR = 1.0) considering the existing fishery, and with L_{50} = 45cm implausibly low, as the fishery would be unlikely to be continuing with such low levels of SPR (< 0.04).

3.4. Indonesia

Throughout Indonesia generally, the value of neritic tuna landings places it within the top ten seafood commodity groups, second only to grouper amongst the teleosts on that list. Neritic tuna are ~51% of the catch of large pelagic fish around the Riau Islands, in the southernmost region of the SCS, Indonesia's Fisheries Management Area 711, where our sampling occurred (Figure 1). Throughout that region the neritic tuna are caught using fishing gear such as purse seine, drift gill net, hand line, troll line, and pole and line (huhate). The purse seine and drift gill nets land most of the neritic tuna catch. The other techniques are used by small-scale operations. For example, at the Nusantara Fishing Port at Pemangkat in the sampled area, the drift gillnet fleet lands 84% of the neritic tuna catch, approximately half of which is Kawakawa; the purse seine fleet lands most of the remaining neritic tuna catch (Wujdi & Suwarso, 2014).

Unable to find catch size composition data for Kawakawa from this region, the program begun by the CFRA to collect Skipjack Tuna size composition data in the marketplaces, was re-purposed for Kawakawa. Data were collected from three local markets (Natuna, Anambas, and Bintan) in the Natuna Islands (4.0°N; 108.25°E), Riau Islands Province, off the northwest coast of Kalimantan. Some 714 fish were measured ranging in length from 35.6-50.2 cm (Figure 7).

The preferred Indonesian estimate of size of maturity for Kawakawa L_{50} = 44cm, seems large for this sample of fish, but is probably based on a study conducted in Bali (Arnenda et al. 2021) and perhaps more appropriate for Kawakawa stocks fished around the southern island chain where cooler oceanic conditions prevail.

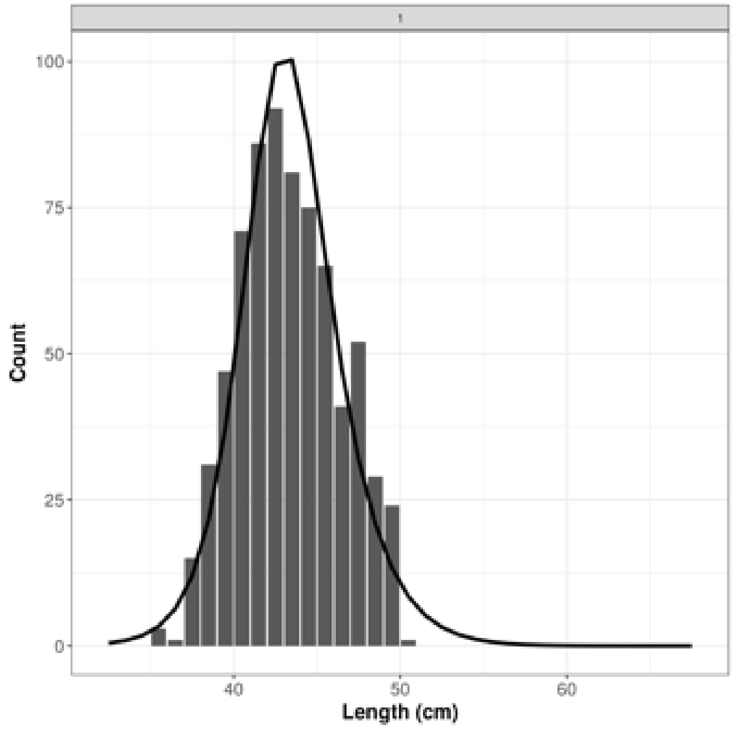


Figure 7. Length-frequency histogram for Indonesian samples of Kawakawa catches.

An average SPR = 0.69 (SD=0.36) was estimated across all scenarios (Table 9). With $L_{50} \leq$ 30cm SPR estimates were implausibly high (SPR = 1.0). With L_{50} =35 - 45cm plausibly lower estimates of SPR resulted (0.22 – 0.92).

Table 9. Estimates of mean SPR derived with the length-frequency data for Kawakawa sampled in markets on the Natuna Islands, Indonesia.

Mean of SPR	**M/K**	**M/K**	**M/K**	**M/K**	
Size of Maturity	**1.00**	**1.05**	**1.10**	**1.15**	**Total**
20	1.00	1.00	1.00	1.00	**1.00**
25	1.00	1.00	1.00	1.00	**1.00**
30	1.00	1.00	1.00	1.00	**1.00**
35	0.89	0.90	0.91	0.92	**0.90**
40	0.33	0.35	0.37	0.39	**0.36**
45	0.18	0.20	0.21	0.22	**0.20**
Total	**0.68**	**0.68**	**0.69**	**0.70**	**0.69**

3.5. China

In China, the CFRA worked with the Fisheries College of Guangdong Ocean University, whose scientists have conducted a port-based program sampling the catches of the pelagic fleet fishing the northern SCS (21.00-22.25°N and 111-115°E) from Guangdong (Figure 1). Purse seine fishing ceased in this region more than a decade ago. The fleet now mainly fishes with light-falling net fishing (Prince et al. 2023a).

The in-port sampling program involved 6-10 days sampling per annum, primarily during one or two weeks of August, or May (over two years), months during which we would expect adult size classes to be catchable (Williamson 1970). Some 988 Kawakawa were measured across the years; 2016, 2017, 2018, 2019, 2020 and 2021.

3.5.1 Time Series Analysis

Unlike the other datasets which appeared trendless across sampling periods. When the Chinese data were aggregated into sequential pairs of years, to portray temporal change and maintain reasonable sample sizes it is observed that (Figure 8):

- The main largest size class (>50cm) of fully adult (2+) fish observed by Williamson (1970) was not recorded in any year (Figure 5 cf. Figure 3).
- In the 2016-17 data some individual 37cm and 47cm fish provide some trace of the smaller 40-50cm, sub-adult 1+ cohort observed in some numbers by Williamson (1970). This remnant of a cohort is not observed in subsequent samples
- By 2018 all mature sizes classes have disappeared from samples.

- By 2020-21 the larger sub-adult size classes (> 30 cm) have also disappeared and the abundance of the main juvenile mode (25-27 cm) is greatly reduced.

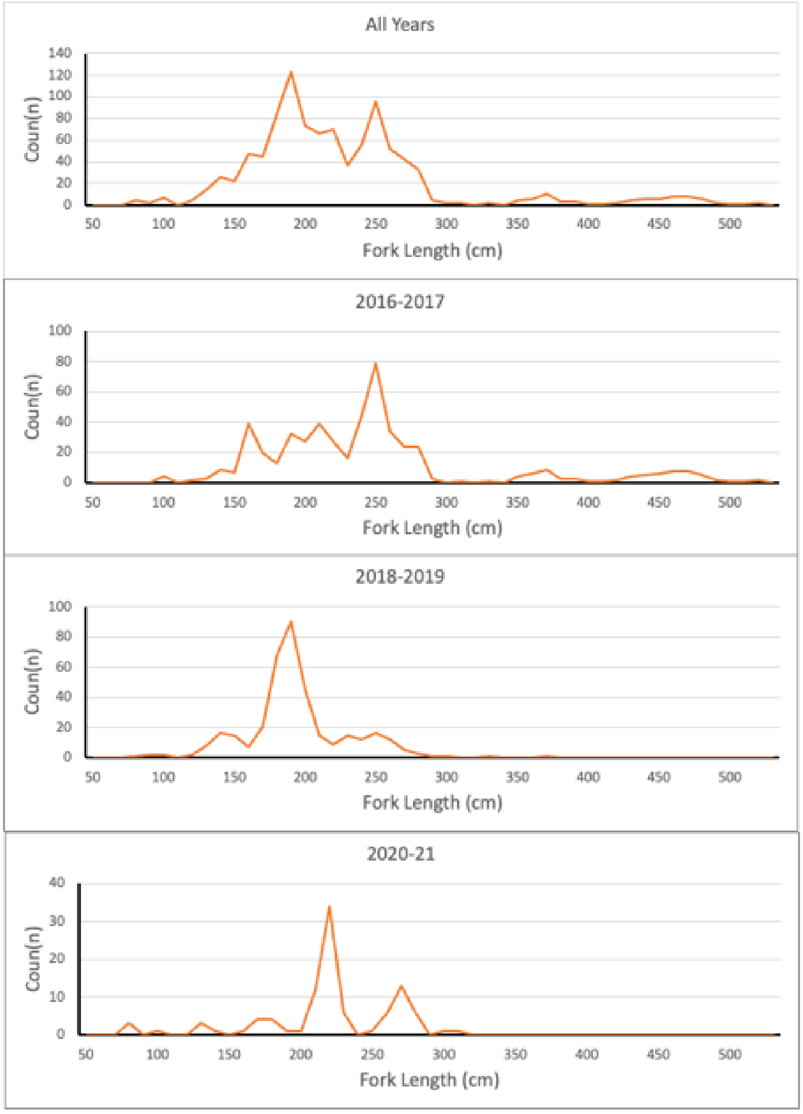


Figure 8. Length-frequency histograms for Kawakawa caught by the Chinese pelagic fleet fishing in the South China Sea.

3.5.2 Estimates of Spawning Potential Ratio

No matter which combination of input assumption are used with these data, all SPR estimates were zero, consistent with the apparent declining abundance of even the smallest juvenile size classes observed over time in these data.

Table 10. Estimates of mean SPR derived with the length-frequency data for Kawakawa from the Chinese catch sampling program in Guangdong.

Average of SPR	**M/K**	**M/K**	**M/K**	**M/K**	
L50	**1.0**	**1.1**	**1.1**	**1.2**	**Grand Total**
20	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0	0.0
35	0.0	0.0	0.0	0.0	0.0
40	0.0	0.0	0.0	0.0	0.0
45	0.0	0.0	0.0	0.0	0.0
Grand Total	0.0	0.0	0.0	0.0	0.0

4. Discussion

4.1 Synthesis of Results

The mean SPR estimates for the Kawakawa stocks off Indonesia, Malaysia, Philippines and Vietnam (0.40-0.81) are indicative of sustainable fishing pressure being applied by traditional fisheries to the sub-adult and adult portion of the stocks. The Chinese data indicate a completely different state. All analysed scenarios suggest there is no longer any spawning potential (SPR ~0.0) in the area fished by the Chinese pelagic fleet. The time series presented suggest the local stock of Kawakawa disappeared progressively from that area over the period 2016-2021. Previously this CFRA inferred that the adult Skipjack Tuna stocks in the northern SCS had been extirpated, but could not exclude counter-arguments to the effect that the region was only ever a nursery area from which adult catches could never have been expected (Prince et al. 2023a). We have Williamson's (1970) study, documenting spawning aggregations of Kawakawa forming seasonally along the coastline near Hong Kong. In addition, the time-series presented shows adult size classes were sampled until 2016-2017, when they disappear subsequently, followed by the sub-adult size and juvenile size classes. The increasingly scarce juveniles are presumably now recruiting through larval transport from more distant and still extant spawning stocks (Figure 8).

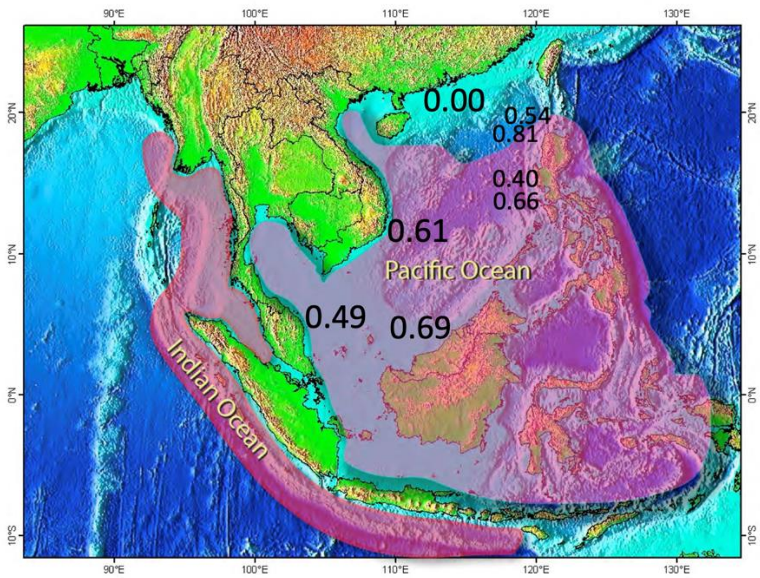


Figure 9: Mean SPR estimates for the Kawakawa stocks off Indonesia, Malaysia, the Philippines, Vietnam, and China visualised on a map.

Admittedly, there are known drivers of change in the SCS, which might still be used to explain the disappearance of Kawakawa from this northern region. Climate change (Venegas et al. 2017; Zhang et al. 2022) and environmental degradation (Zhang et al. 2020) for example; which cannot be fully taken into account with our data-limited framework of assessment. The likely impact of climate change on our results is perhaps most easily addressed as modelling of Skipjack Tuna in the SCS suggests that the spawning sites of neritic tuna should shift away from equatorial regions, rather than retreating from higher latitudes (Venegas et al. 2017). The issue of environmental degradation cannot be so simply addressed and must be acknowledged, although the impact of primarily coastal environmental issues on the pelagic shelf environment that supports neritic tuna is likely to be relatively minor probably compared to the major changes observed broadly across the fisheries in this area (Zhang et al. 2020), or the change in nektonic species composition we infer.

4.2 The Race for Fish leading to Fishing Down Food-webs

China's fisheries resources have been over-exploited since the 1970s and large declines in biomass and Catch Per Unit Effort (CPUE) have occurred in the northern SCS over the past six decades (Zhang et al. 2020). Un-managed fishing pressure motivates a damaging 'race for the fish' as fishers compete to maximise individual shares of the catch. Across disparate fisheries and jurisdictions, this 'race for the fish' motivates the competitive development of fishing gears, targeting practices, and vessels. More efficient methods are being developed initially to target the most valuable adult and sub-adult sized fish, but as the larger and more valuable fish become scarcer, these methods change progressively to fishing for smaller and smaller juvenile size classes as well (Rosenberg 2017; Prince et al. 2020; Zhang et al. 2020; Sun & Chen 2023). In multi-species fisheries the race for the fish results, over-time, in 'fishing down the food-web' (Pauly et al. 1998) a characteristic pattern of trophic change in catch composition: from a predominance of a few medium to relatively large-sized, high-value, high trophic level, demersal species targeted with selective techniques, to purposefully unselective fishing gears catching many small, low-valued, short-lived, low trophic level species (Cao et al., 2017; Liu & Sadovy de Mitcheson, 2008; Lundgren et al. 2006; Pauly et al. 1998; Shen & Heino, 2014; Zhang et al. 2020; Sun & Chen 2023).

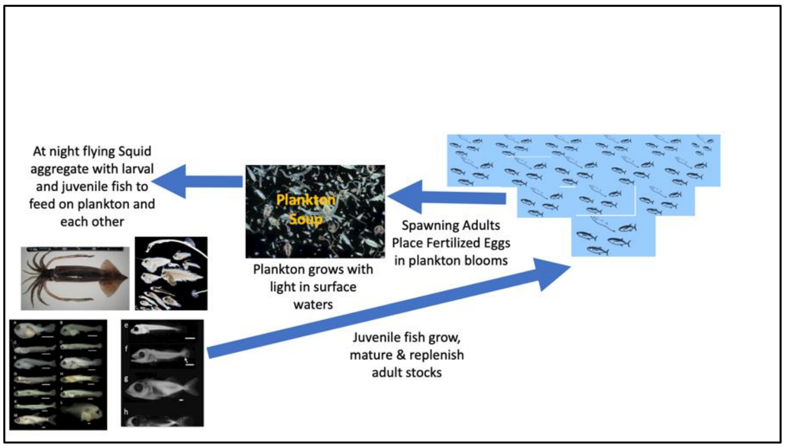
Since the 1990s on-going over-fishing in the northern SCS has incentivised fisheries production shifting away from directly supplying seafood for human consumption, towards supplying feedstock for aquaculture (Zhang et al. 2020; Sun & Chen 2023). This change has been associated for the last two to three decades with the expansion of the fishing technique called light-falling net fishing (Chee 1992; Wu et al. 2016) a purposefully unselective method of fishing gears catching small, low-value, short-lived, low trophic level species, in itself a symptom of the intense race for fish that has been occurring in the northern SCS.

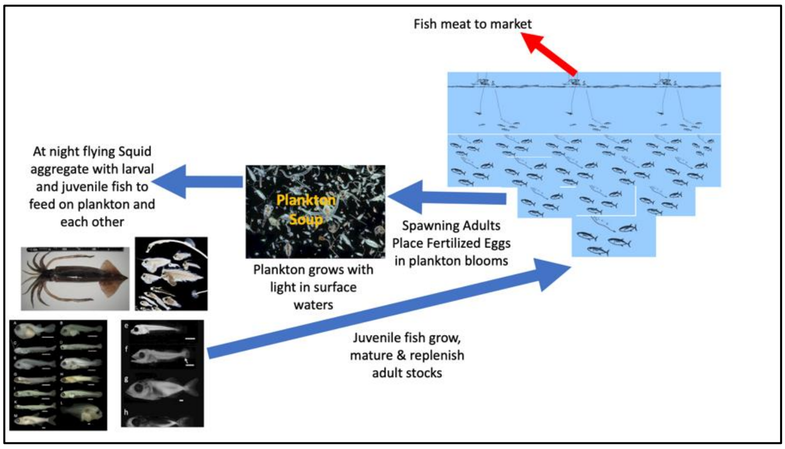
4.3 Light-Falling Net Fishing

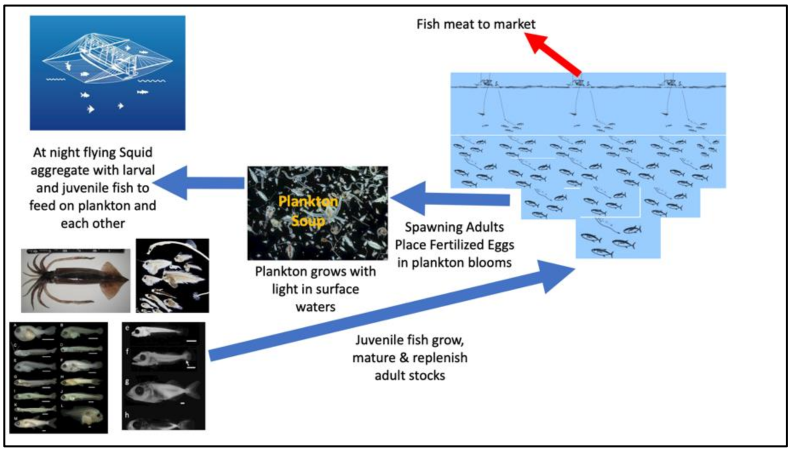
Light-falling net fishing (Wu et al. 2016) involves using strong lights to attract surface swarms of zoo-plankton around vessels at night (Figure 10), which in turn attracts the larvae and juveniles of the neritic tunas and Mackerel Scad (*decapterus maruadsi*) that predate upon the zooplankton, as well as the purpleback flying squid which prey upon all the larger members of this nektonic assemblage (Xinjun et al. 2007). Light-falling net fishing involves periodically enveloping the entire aggregation of nektonic biomass with a large fine-mesh drop-net, which is then pursed at the bottom (Pauly and Chuenpagdee 2003; Wu et al. 2016). Described as 'biomass fishing' by Teh et al. (2019), larval and juvenile fish can comprise 35-40% by weight of landings, and is sold for reduction primarily into aquaculture feeds (Teh et al. 2019; Zhang et al. 2020; Sun & Chen 2023).

Chee (1992) describes the previous replacement of artisanal fishing techniques such as handlining, trolling and coastal barrier nets in many parts of the SCS, with industrial drift gillnetting and purse-seining: techniques which in turn have been replaced by light-falling net fishing (Pauly and Chuenpagdee 2003; Wu et al. 2016; Teh et al. 2019), not only in China (Cao et al., 2015; Funge-Smith et al. 2005; Lundgren et al., 2006), but also in Vietnam (Edwards et al. 2004) and other countries (Funge-Smith et al., 2005).

The development and expansion of this un-selective 'biomass fishing' technique marks a new low point in the fishing down of the SCS food web (Teh et al. 2019; Zhang et al. 2020; Sun & Chen 2023) which has enabled fisheries to remain economically viable overfishing for longer (Zhang et al. 2020; Sun & Chen 2023). In China there has been an emphasis on levels of gross production, which has remained relative stable, because production from light-falling net fishing has masked the decline of CPUE, biomass, and fish sizes, and eventual loss of food fisheries, primarily driven by severe overfishing, and excessive capture of larvae and juveniles (Zhang et al. 2020). The expansion of aquaculture globally has helped fill the gap between seafood supply and demand, and contributed to economic development around the region. East Asia accounts for ~62% of global aquaculture production, and five of the top ten global aquaculture producers are SCS countries (Teh et al. 2019). At some stage, however, the supply of fish meal from wild fisheries must be limited by the capacity of those stocks to continue supplying larval and juvenile fish (Figure 10). The data presented here suggest that that limit has now been passed in the northern SCS.




Fish meat to market
At night flying Squid aggregate with larval and juvenile fish to feed on plankton and each other
Plankton Soup
Plankton grows with light in surface waters
Spawning Adults Place Fertilized Eggs in plankton blooms
Juvenile fish grow, mature & replenish adult stocks


Fish meat to market
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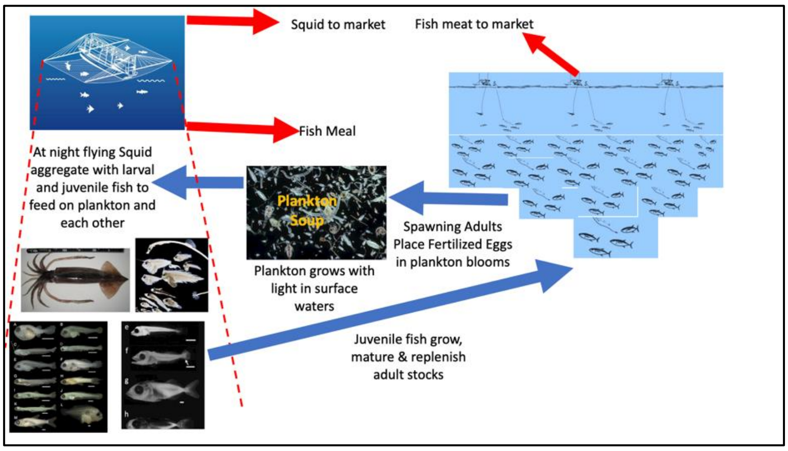
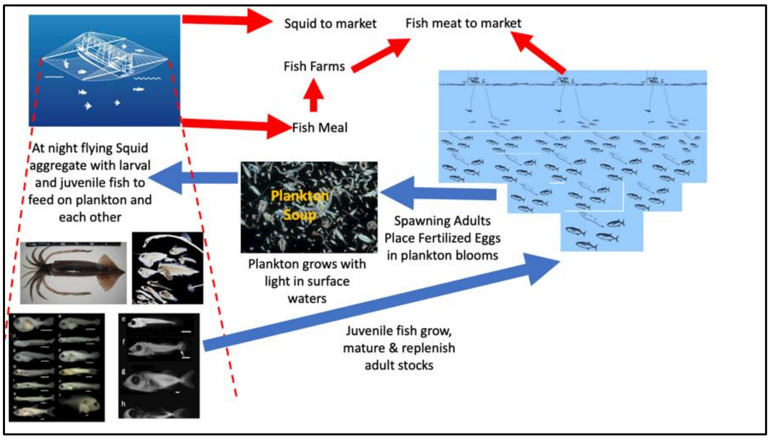

Squid to market
Fish meat to market
Fish Meal
At night flying Squid aggregate with larval and juvenile fish to feed on plankton and each other
Plankton Soup
Plankton grows with light in surface waters
Spawning Adults Place Fertilized Eggs in plankton blooms
Juvenile fish grow, mature & replenish adult stocks


Squid to market
Fish meat to market
Fish Farms
Fish Meal
At night flying Squid aggregate with larval and juvenile fish to feed on plankton and each other
Plankton Soup
Plankton grows with light in surface waters
Spawning Adults Place Fertilized Eggs in plankton blooms
Juvenile fish grow, mature & replenish adult stocks

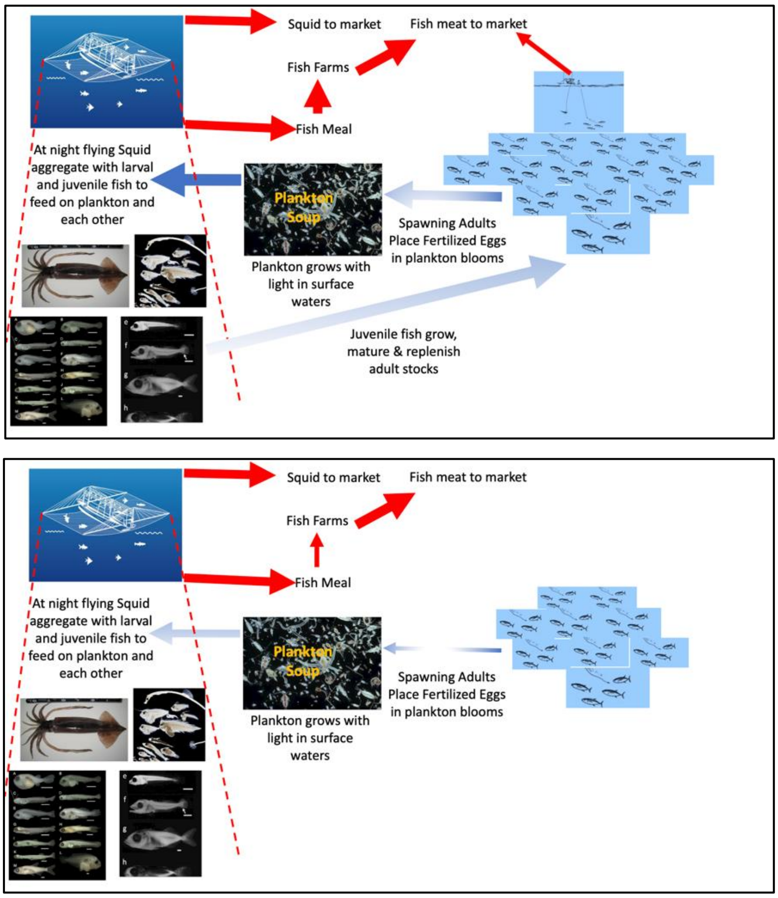


Figure 10. Illustration of the 'larval commons', which supports traditional fisheries which primarily target sub-adult and adult size classes of fish and squid and which is targeted directly by light-fall netting, which exacerbates recruitment overfishing of sub-adult and adult stocks and results in the displacement of traditional fishing techniques.

4.4 Sustainability Through Selective Fishing

Fisheries science has traditionally recognized two distinct forms of overfishing (Beverton & Holt 1957); The first, 'growth overfishing', results in the gross under-valuing of stocks, by catching juvenile and sub-adult fish before they fulfil their adult growth potential, but can be corrected relatively quickly over several seasons by reducing fishing pressure. The second, 'recruitment overfishing', reduces the recruitment (supply of larvae and juveniles) required to sustain adult populations, is more serious because the long-term depletions caused require multiple generations to reverse (i.e. usually decades), and if not corrected results eventually in local extinctions. Catching the larval and juvenile size classes of fish with light-falling net fishing implicitly involves both growth and recruitment overfishing, ensuring sub-optimal yields from these fish species, and heightening the risk of recruitment collapse and local extirpations. Where fishing pressure on adults is already significant, the fishing of larvae and juveniles with light-falling nets will be particularly likely to drive recruitment over-fishing and the extirpation of local populations [Figure 10], which the data presented shows has occurred in the northern SCS.

4.5 The Larval Commons

Juvenile neritic pelagics are 'recruited' from pelagic larvae. After hatching from eggs released and fertilized at spawning aggregations, the larvae spend some weeks to months drifting with prevailing currents, hunting within a species assemblage of plankton and nekton (larger bodied pelagic animals that prey upon plankton) that forms a dispersed inter-connected network along coast lines and across chains of reefs and islands. While most larval fish probably do not travel far from natal sources, there is sufficient dispersal to maintain long-term genetic connectivity through the meta-populations that comprise each species range. This dispersion of planktonic and nektonic biomass will have particularly productive locations, or 'hot-spots', where some combination of geographic and oceanographic features enhance the upward mixing of nutrients through the water column regularly enriching phytoplankton productivity (Zainuddin et al. 2017). These locations are selected as spawning sites by marine species because the enriched plankton enhances larval survival, and the concentration of the larval and juvenile fish that results will attract feeding aggregations of flying squid (Xinjun et al. 2007). This multi-species dispersion of plankton, larvae, juveniles and sub-adult fish and squid, is in effect a 'common-pool resource' (Ostrom 1990) that the various fisheries depend upon to support production for their fisheries (Figure 10). In the context of South American scallop fisheries it has been referred to as a 'larval commons' (J.M. Orensanz, Pers. Comm.).

What we are witnessing in the SCS is another form of the tragedy-of-the-commons (Hardin 1968) and competition to extract value directly from the 'larval commons' by fishing at night with lights and small mesh nets before the resource can grow into fish directly for human consumption. A purposefully un-selective fishing method is impoverishing the larval commons' potential to support the adult stocks relied upon by other fisheries. By directly targeting the larval biomass and cutting off the supply of juveniles and sub-adults to other fisheries, un-managed fishing with light-falling nets inevitably out-competes and displaces more traditional fishing methods.

We infer that after decades of heavy un-selective fishing pressure, large scale systemic changes have been occurring in nektonic communities of the SCS, and in the northern part there is no longer functioning populations of neritic pelagics, and that this is the reason traditional fishing methods for targeting adult and sub-adult neritic pelagics have not been practiced in that region for some years, or decades. We would expect that such large changes in the composition of nektonic predators would have the potential to catalyse systemic ecosystem instability and the results of Zhang et al. (2022) could be re-interpreted in this context. Reporting on trends in the composition of coastal trawl surveys, they observed that two species of small coastal pelagic fish which provided stable yields prior to 1990, while declining significantly in abundance, had become dominant in catches (increasing from being <20 % to 55-70% of catches between 1990 and 2008-11) and since the early 2000s had also begun fluctuating dramatically with climatic events. Zhang et al. (2022) were most focused on discerning the potential impacts of climate change in their data, but given that the species in question are primary prey species for neritic tunas, the dramatic variability they observed might be expected in species that are simultaneously being fished heavily and released from predation pressure, through the overfishing of their main predators.

4.6 The Larval Frontier: An On-going Source of Conflict

Un-managed the fishing pressure by light-fall netting will inevitably cause its own disruption in any location by recruitment overfishing of the local sub-adult and adult stocks of the neritic pelagics, diminishing supplies of the larval and juvenile fish (Figure 10) that are the main prey of the flying squid (Xinjun et al. 2007). With depleted supplies of larger items of prey the productivity of squid populations will also decline, or squid will move away to where prey remain plentiful. We conceive of the SCS larval commons resource as exhibiting a concentration, or depletion, profile (Clark 1982), radiating out from the major ports and markets for fish-feed production (Caddy 1975; Prince & Hilborn 1998). A profile created by the differential costs and benefits of travelling to distant fishing grounds, with lower costs, higher fishing pressure and lower catch rates, close to major ports and markets, and higher costs and returns incurred by fishing remote fishing grounds. Without effective management, fishing pressure close to ports only ever ratchets higher, driving the sequential depletion and localised extirpations of component stocks within meta-populations (Prince & Hilborn 1988) as exemplified by our Chinese data.

Conceptualised as a concentration profile, the effect of serial depletions of component sub-populations within the larval commons will be to create frontal regions; transition zones between areas with extant adult populations producing normally high larval concentrations and areas heavily exploited with light-falling net fishing and depleted levels of larval and juvenile neritic pelagics (Figure 11). The best 'biomass fishing' will always be in areas with extant adult fish populations producing the larval and juvenile fish that attract and support larger squid. Subject to the greater cost of fishing further afield, light-falling net vessels will be attracted to fish around areas with extant adult fish populations. Fishing too far away from larval sources, *behind* the larval front, with lower catch rates of squid and fish biomass, will be commensurately less profitable. The current economic distress of the Chinese pelagic fishery in the northern SCS, relayed anecdotally to the CFRA, suggest this harsh reality is now impacting this fishery.

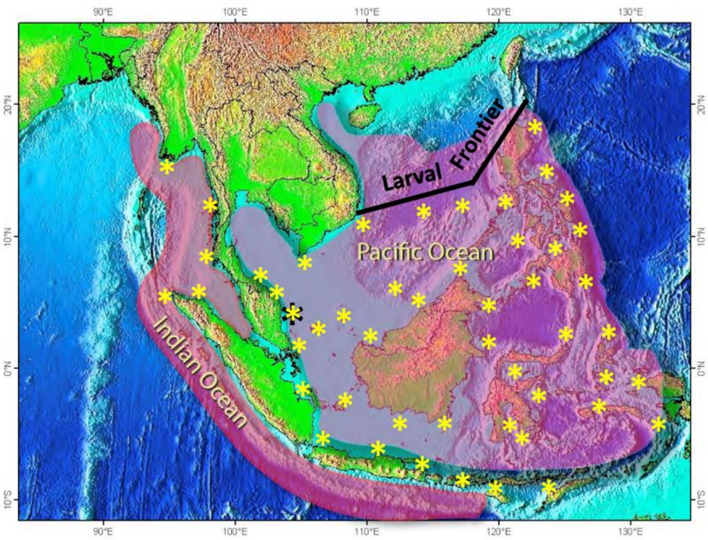


Figure 11. Illustration of the 'larval frontier' between regions with extant spawning stocks continuing to produce the eggs and larvae which supplement the zoo-plankton communities that comprise the larval commons, and regions in which the spawning stocks of neritic pelagic fish communities have been extirpated. The light-fall fishing fleet which has exacerbated recruitment overfishing behind this frontier will be attracted to fish along this frontier by the potential for higher catch rates, creating an on-going source of conflict with the traditional fishing fleets it displaces by targeting the larval commons, which exacerbates recruitment overfishing.

While our data suggest that the depletion of the larval commons is currently confined to the northern SCS, we do not expect this situation to remain static. Rather, with the light-falling net fleet being attracted to fish close to larval fronts, in and around areas with extant adult stocks and viable traditional coastal fisheries, but then exacerbating the loss of fisheries productivity in those regions by depleting the larval commons. We expect the area with depleted larval commons, and the larval frontier to continue receding away from the main home ports of this fleet, and for the depleted areas to continue growing. That process will, in turn, motivate the fleet to travel further out to find areas with good concentrations of fish larvae and squid, where without effective management, it will continue out-competing and displacing the more traditional coastal fisheries they are attracted to fish alongside. This progressive extension of the range of the light-fall fishery following the contracting larval frontier, and their on-going displacement of traditional fishing fleets, will remain an on-going source of tension in SCS. In the absence of effective management we expect that the receding larval frontier will continue to provide flash-points for conflict between national fishing fleets. Effective management to sustain the potential yield from parental stocks, and the ongoing supply of biomass for fishmeal, will be necessary to stabilise this situation.

4.7 Beyond Ending Subsidies for Fishing Fleets

Focused on national development instead of environmental sustainability, the fishing fleets of the SCS have received about 30% of global fishing subsidies (Sumaila and Cheung, 2015) which has created substantial overcapacity, and continued over-exploitation of its depleted resources (Milazzo 1998; Sumaila et al. 2010). In line with the 2022 World Trade Organization (WTO) Agreement on Fisheries Subsidies reached, the SCS nations have taken significant steps towards removing subsidies for fishing: the Philippines no longer has any subsidies for fishing, only some assistance for vessel maintenance; Vietnam and China ended fuel subsidies in 2022; Indonesia and Malaysia now only offer fuel subsidies to small scale-fishers (under 10 gross Tonnes and 70 gross registered Tonnes, respectively). Although their removal alone will not address the degraded and depleted state of its marine resources, the process of eliminating all fishing subsidies should be completed.

4.8 Effective Co-ordinated Sub-Regional Fisheries Management

Effective fisheries management, applied with co-ordination, across-scales and jurisdictions in the SCS will be required to restore the functioning of these marine ecosystems and rebuild lost productivity. While continuing to independently manage resources in their own waters, the

SCS nations should agree to act in parallel to achieve shared aims for resource sustainability and optimisation. Similar to the assessment model being piloted by the CFRA, the SCS nations face similar fisheries management issues. If addressed independently in parallel by joint agreement, compatible fisheries management would be applied throughout the SCS regardless of jurisdictional disputes, and end up achieving shared communal benefits for all.

While it is theoretically possible to maximise biomass yields with a ‘balanced harvest’ across the entire size spectrum of multi-species ecosystems – such as the SCS nektonic biomass (Sun & Chen 2023) – so that a sustainable light-falling net fishery is theoretically conceivable, in reality, achieving a sustainable balanced harvest will require a higher degree of effective monitoring and management than is feasible in the data-limited SCS context (Sun & Chen 2023).

Instead, the SCS nations should aim to achieve sustainability more simply by working together to systematically modify and regulate fishing gears and techniques throughout the SCS, so as to more selectively target valuable species and size classes, while minimizing incidental catches of lower value sizes and species, and in this way make stocks everywhere more resilient to growth and recruitment overfishing.

Planned reductions in fishing fleet and effective fishing effort are required throughout almost the entire SCS, but noting that fishing intensity varies considerably across the region (Wu et al. 2024), each nation’s target for capacity reductions will also vary, and will need refining over time. Regions where marine food-webs have been fished down most heavily will require greater reductions in fishing capacity to restore optimal eco-system functioning. The SCS nations should work in parallel and together to develop and implement agreed harvest strategies enabling the capacity for the adaptive management; pre-agreed systems for monitoring stock abundance in different regions and pre-determined rules for incrementally adjusting fishing pressure, until shared objectives for stock health are achieved everywhere (Smith et al. 2008).

Despite the challenge of sustainably managing SCS marine resources, there is currently no permanent forum to focus on the difficult dialogue required to develop the trans-national cooperation necessary to facilitate effective trans-national management. RFMOs have been widely established to provide multi-national frameworks for facilitating and co-ordinating research, monitoring and management of trans-boundary stocks. The WCPFC, which nominally encompasses the SCS, has made it clear through inactivity, that it lacks the institutional will required to focus on the specific challenges of the SCS. Nevertheless the SCS requires a similar framework to carry on the international co-operation initiated through our CFRA process. Without such a framework for the SCS it is unlikely that more sophisticated methods of resource assessment than ours will ever be possible. The SCS FSWG, in producing two CFRAs on shared stocks, plays a small role in encouraging joint fisheries management in the SCS, but it is not the same as a formal, institutionalised body. Even after constructing such a framework, several decades of research and monitoring will be required to provide the robust science most policymakers desire.

5. Conclusions

This study has conducted basic fisheries studies with the aim of reducing international tensions in a contested region by facilitating and informing international dialogue about the management of trans-national fisheries. While leaving much to be desired from the purely scientific perspective, in terms of unambiguously diagnosing biomass trends, our regional analysis has identified important trends that should concern regional policymakers. While the growth of aquaculture has helped fill the gap between supply and demand for fish, and contributed to economic development in the region, the sustainability of 'biomass fishing' to supply the feedstock of aquaculture will ultimately depend on sustaining the adult stocks of fish required to produce the biomass of larval and juvenile fish larvae being extracted. The evidence presented here suggests that the nektonic biomass in the northern SCS has been depleted to the extent that regional stocks of neritic tuna have been extirpated.

We recommend:

- Building on the CFRA to regularise cooperation between government and non-government fisheries scientists among SCS coastal states. This cooperation should build a shared evidence base for agreeing on compatible parallel approaches to managing within each country's jurisdiction the shared fish stocks.
- The SCS nations work in parallel to implement and enforce agreed standards for fishing gears and techniques that improve the size and species selectivity of fishing so as to make stocks resilient to growth and recruitment overfishing.
- The SCS nations continue cutting subsidies for fishing fleets to nothing,

- The SCS nations work in parallel to update policies to initially cap the number, size of vessels, and amount of gear deployed, so as to stop any further expansion of fishing capacity,
- The SCS nations work in parallel to develop and implement plans for phased long-term reductions to national fishing capacity.
- The SCS nations work in parallel to develop and implement harvest strategies for adaptive and incrementally adjusting fishing pressure in relation to regional stock abundance, so as to achieve shared objectives for stock health everywhere.

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7. Conflict of Interest Declaration

The authors have no competing interests to declare.

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