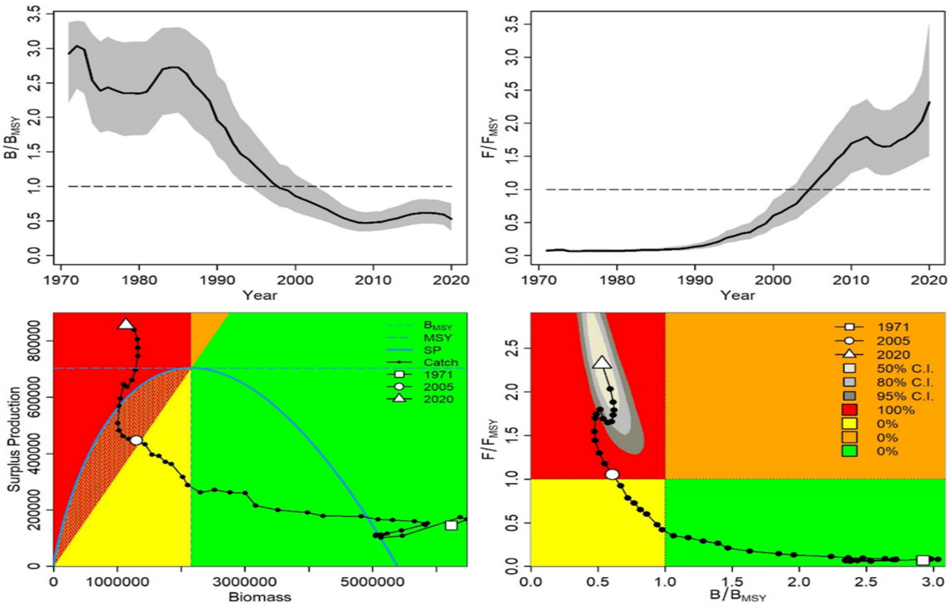
Stock Assessment Methods For Multispecies Fisheries



A guidance document for the Vung Tau Fisheries Improvement Project

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1. Introduction[1]

As part of the Fisheries Action Plan (FAP) that was developed to address the gaps identified in the MarinTrust fishery assessment carried out in July 2021, action 2.2.1.1 is to provide guidance on "Stock assessment methods for multispecies fisheries". The aim of the guidance was to set the background for (i) a workshop to identify gaps in the past assessments and plan future assessments, (ii) conduct stock assessments based on existing and new data and input into the FMP. These assessments then feed into the development of mitigation measures as part of a fisheries management plan (FMP).

The report considers:

1. Role of stock assessment in fisheries management;
2. Single-species stock assessment data needs and options;
3. Multi-species stock assessment data needs and options;
4. Single-species or multi-species assessments?

[1] Acknowledgement: Much of the material for this report is taken from Amoroso (in press), Fulton (in press), Leadbitter et al. (in press) and (Staples et al. (in press). Full citations are in the reference list.
[2]A bell-shaped curve that is used to describe this relationship shows that there is a surplus production that can be harvested without reducing the stock abundance. The long-term sustainable catch is the maximum sustainable yield (MSY).

2. Stock Assessment And Fisheries Management.

The central theorem of fisheries management is that there is a relationship between fish abundance and the long-term sustainable catch for any fish stock in a given fishery (Figure 1).

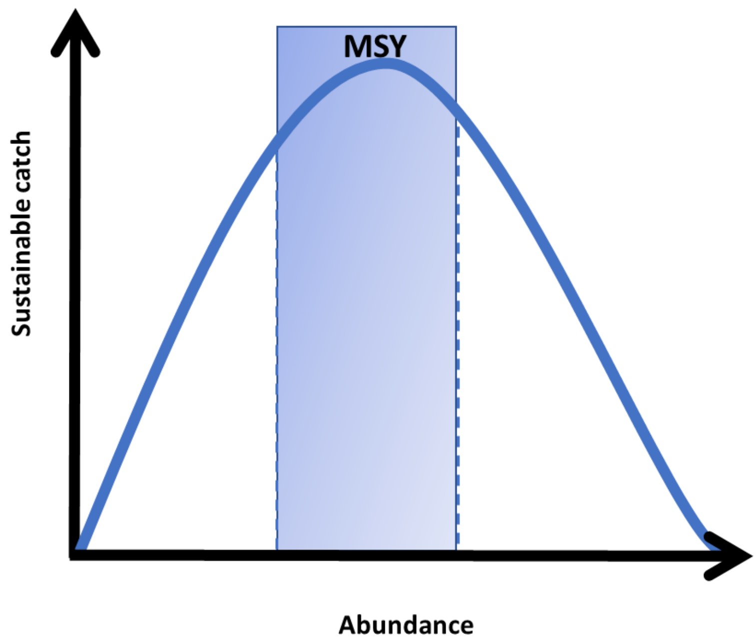


Figure 1: Relationship between fish abundance and the long-term sustainable catch. Blue shaded area shows where catch and/or effort management measures can be used to control abundance to optimize economic and social benefits. MSY = maximum sustainable yield. *Source: Modified from Amoroso (in press)*

Based on this theorem, one of the main goals of effective management is to keep stocks within a specific range of abundance. This can be achieved by (i) controlling the catch e.g. a total allowable catch (TAC), and/or (ii) controlling the fishing effort (total allowable effort [TAE) and/or (iii) by a range of technical measures such as closed areas and/or seasons, controlling the mesh size of the fishing gear, limiting the size of the fish that can be caught etc. The desired level of catch depends on the tradeoffs of a number of multiple objectives - maintaining high catches to improve food security, allowing the catch to decline but maintain maximum employment and livelihoods, optimizing the economic returns from fishing and preserving ecological integrity.

However, before we can control the level of abundance in a fishery we need to know the current status of the resources. This can be achieved through conducting a stock assessment as part of three steps of a management cycle (Figure 2):

1. Data collection
2. Stock assessment
3. Management actions/measures

Figure 2: Diagram of the fisheries management cycle showing the link between data collection, stock assessment and management actions. *Source: Amoroso (in press)*

Stock assessments require:

1. A long-term monitoring program.
2. Regular stock assessments that estimate the values for key indicators of the fishery's status (e.g. level of fishing, fish abundance, economic return and livelihoods) and population health.
3. Setting of targets and limits on harvesting - usually target and/or limit reference points for fishing mortality rates or abundance/biomass.
4. Agreeing on harvest control rules: what to do when the indicators do not align with the reference points.

3. Single-Species Stock Assessments

3.1. Data Needs For Single-Species Stock Assessments

There is a wide range of stock assessment methods available. To a large extent, the method that is used for a particular fishery depends on what data are available, which can range from data poor (very little information) to data rich (fisheries with a age structured data and data that is independent of fishery and includes detailed information on biology and ecology) – the gold star of data and stock assessment (Figure 3).

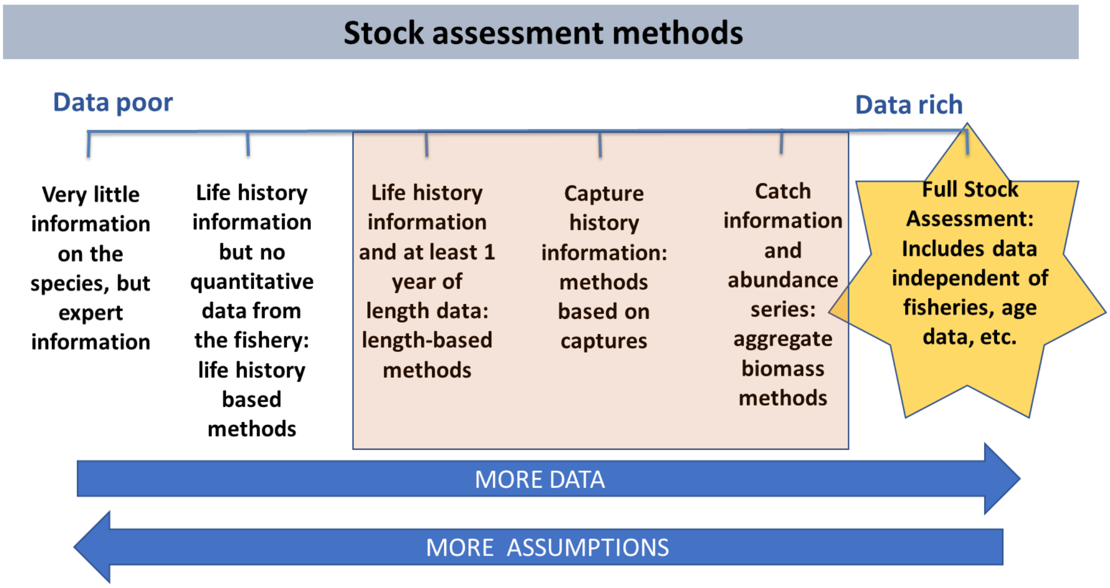


Figure 3: The range of data needed for different single-species stock assessment methods spanning data-poor to data-rich fisheries. *Source: Amoroso (in press)*

Only a limited number of stock assessments have been carried out in Southeast Asia because it was thought that the region did not have enough data to fully cover the complex multi-species/multi-fleet fisheries of the region. However, more and more methods are being developed for data-poor situations and there is a greater access to these methods through open access assessment tools. Also, there is often more data than originally thought if we look in the right places, and for most fisheries in Southeast Asia (including Viet Nam), there is usually some data that lies somewhere in the pink box in Figure 3 ("data-medium" fisheries).

Although data-poor methods are becoming increasingly available, the model assumptions and uncertainty in the model predictions in these types of assessments is greater than in data-rich situations), as shown by the bottom arrow in Figure 3. Thus, more care is needed in testing the assumptions and examining the uncertainty in these data-poor situations.

3.2. Single-Species Stock Assessment Options

The main methods that can be used in the case of "data-medium" situations typical of Southeast Asia are:

1. Production/biomass dynamic models
2. Catch-only methods
3. Length-based methods

3.2.1 Production /biomass dynamic models

Model structure

The underlying logic of a production/biomass dynamic model is:
[New biomass] = [Old biomass] + [Production] – [Catch]

$$B_{t+1} = B_t + P_t - C_t$$

where:
Production = somatic growth + recruitment - natural mortality,
which can be calculated as:

$$P_t = rB_t\left(1 - \frac{B_t}{K}\right)$$

Where r = intrinsic rate of population growth and K = carrying capacity, and B_t = biomass at time *t*.
Substituting for P_t results in:

$$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right) - C_t$$

As shown in Figure 4, as the biomass declines as a result of fishing, the population's production increases up until a maximum, after which it declines again.

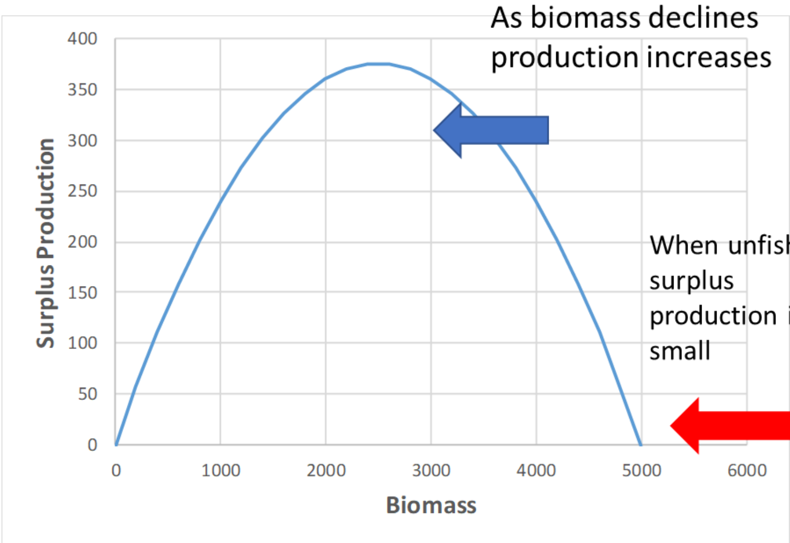


Figure 4: Basis for the production/biomass dynamic model for assessing fish stocks. *Source: Amoroso (in press)*

By fitting the model to a time series of catch and relative abundance, we can estimate the values of the parameters r and K. The model can then provide estimates of total abundance. fishing pressure, status of the fish stock and reference points such as the virgin biomass ($B_{o)}$, the MSY, biomass at MSY (BMSY) and fishing mortality at MSY (FMSY) (Figure 5):

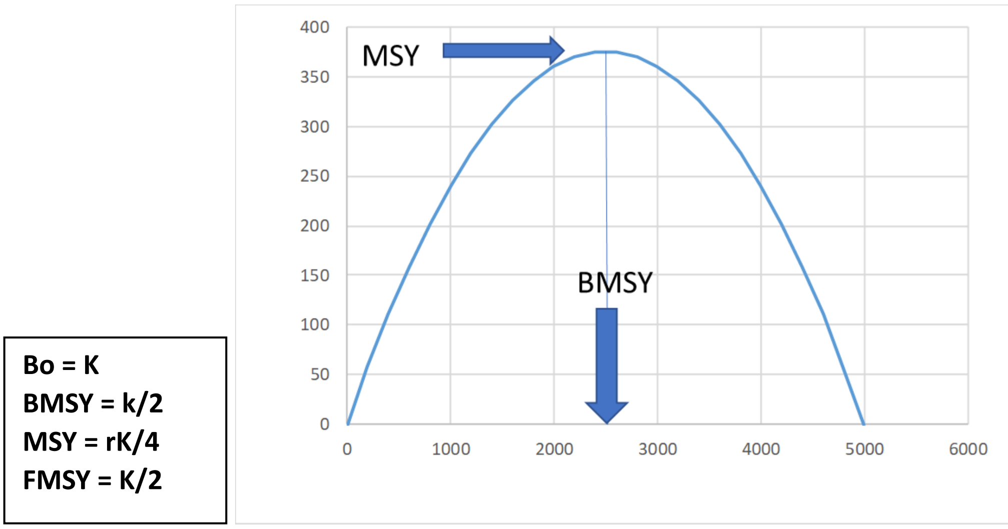


Figure 5: Estimating the maximum sustainable yield (MSY) and the biomass at MSY (BMSY) in a production/biomass dynamic model. B_0 = virgin biomass; K = carrying capacity; r = intrinsic rate of increase; F = fishing mortality. *Source: Amoroso (in press)*

Uncertainties and assumptions in production/biomass dynamic models

Index of abundance not proportional to the true abundance: The model assumes that the index of abundance used to fit the model is proportional to the true population abundance. However, if we use the catch per unit effort (CPUE) calculated from commercial catch and effort data, the CPUE index could reflect hyper-depletion where CPUE declines faster than abundance (using these data in an assessment can produce pessimistic results) or could reflect hyper-stability where the CPUE stays stable while the actual fish population declines dramatically (resulting in an over-optimistic results) (Figure 6).

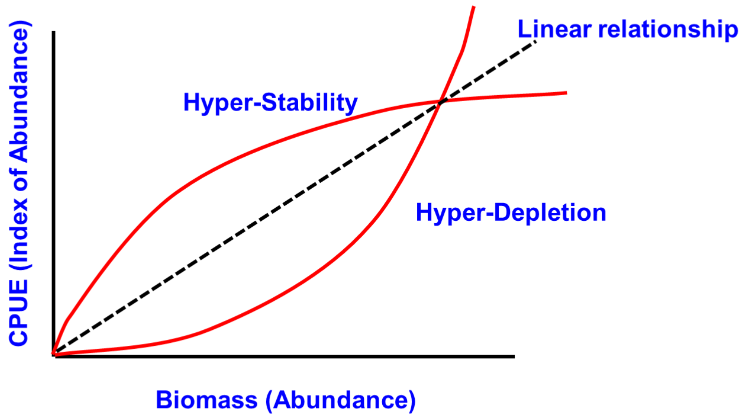


Figure 6: Hyper-depletion and hyper-stability that could occur when the index (e.g. CPUE) is not proportional to abundance.

Biased catch data: Another cause of error is biased catch data resulting from under-reporting, over-reporting or increasing/decreasing rates of reporting during the history of the fishery (Figure 7).

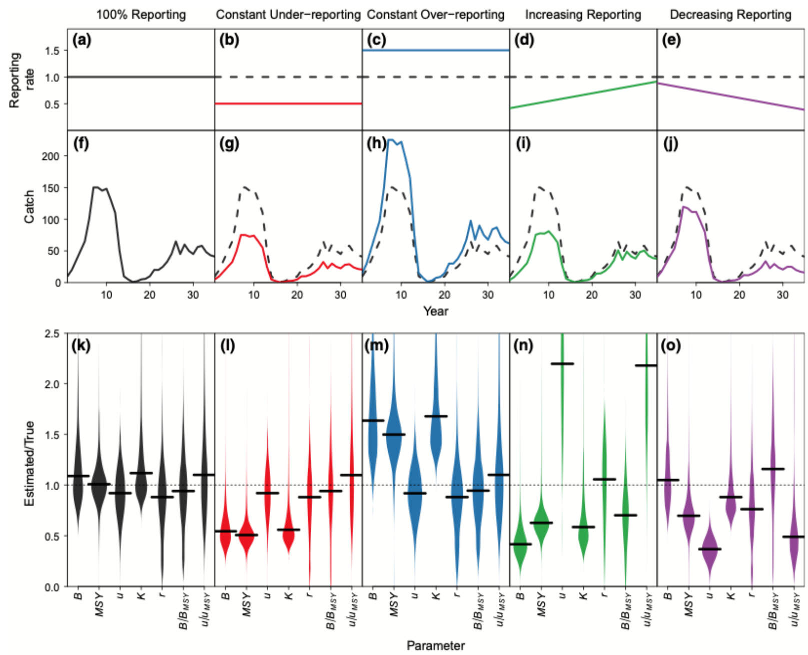


Figure 7: Errors in the estimates of production/biomass dynamic model parameters caused by biases in the catch data. *Source: Rudd et al. 2017*

Changes in productivity: The model assumes that the productivity of the stock does not change over time. However, changes in productivity are known to occur in some fish stocks, example e.g., Atlantic cod *Gadas morhua* in the Iceland fishing grounds (Vert-pre et al. 2013) (Figure 8).

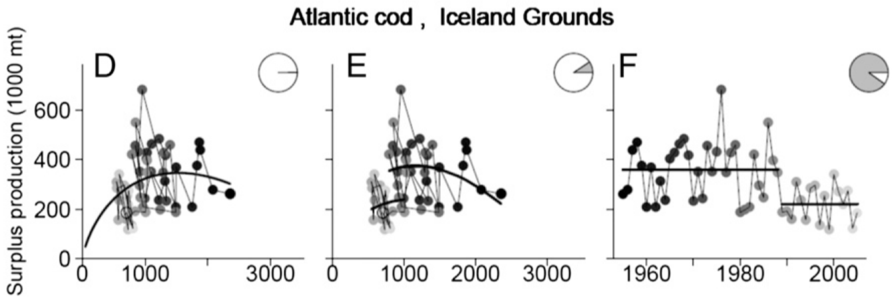


Figure 8: Changes in productivity of Atlantic cod on the Iceland fishing grounds. *Source: Vert-pre et al. 2012*

Lack of contrast: A reliable fit of the model relies on having contrast in the data, with both increases and decreases in catch and abundance. The most common type of time series is increasing fishing effort and declining CPUE. This "one-way-trip" cannot provide enough contrast to reliably estimate the parameters of r and K (see Figure 9 for an example).

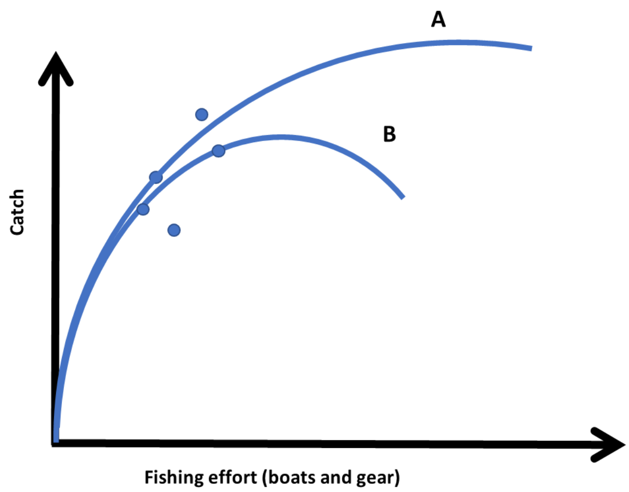


Figure 9: Example of a "one-way trip" where there is not enough contrast in the data to determine whether the stock has reached its MSY or whether there is still room for further expansion of fishing effort.

3.2.2 Catch-only methods

The past history of catches can be used to provide some information of stock status. Pauly et al. 2008 developed the following criteria based on the historical trend in catches (Figure 10):

Developing (catches ≤ 50% of peak and year is pre-peak, or year of peak is final year of the time series);

Exploited (catches ≥ 50% of peak catches);

Over-exploited (catches between 50% and 10% of peak and year is post-peak);

Collapsed (catches < 10% of peak and year is post-peak); and

Rebuilding (catches between 10% and 50% of peak and year is after post-peak minimum).

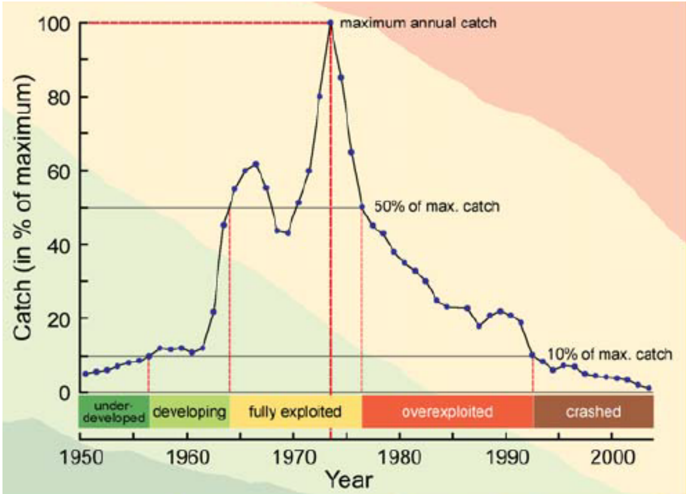


Figure 10: Classification of status of stocks based on catch trends from fishery data. *Source: Pauly et al. 2008*

This simple approach can be better informed by using a production/biomass dynamic model to estimate parameters that can explain the catch history without collapsing the populations. This additional step generates a distribution of r and K as well as reference points such as the MSY. It is then possible to add previous knowledge of r, K and current status as priors to refine the assessment (Martell and Froese 2023) based on expert opinion and/or previous studies. For example the following information was provided by other studies and fishermen's reports - "Based on studies of similar species, the intrinsic growth rate r of this species is probably between 0.1 and 0.5," "Fishermen report that there are far fewer fish today than there were 30 years ago, so we believe that the current depletion is between 0.1 and 0.25". Keeping the combination of parameters that align with our prior information on depletion produces a distribution of reference points and stock status that satisfy the assumptions of the model (Figure 11).

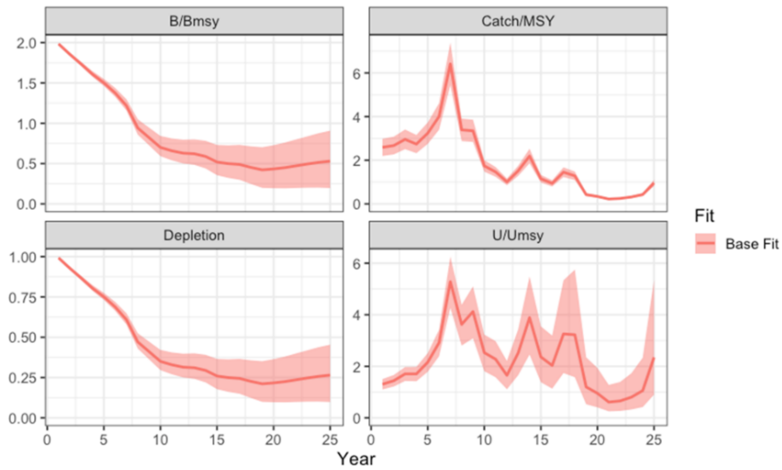


Figure 11: Stock status based on catch-only data informed by expert opinion and results from previous studies.

Uncertainties and assumptions in catch-only models

As with production/biomass dynamic models, there are a number of assumptions and uncertainties that need to be considered.

Sensitivity to the priors: Changes in the prior r and K affects the conclusions about stock status changes. For example, a higher r prior results in a decrease in the depletion of the stock biomass and an increase in the ratio of the biomass to the biomass at MSY (B/BMSY) in later years, as well as a decrease in the fishing mortality (U/UMSY) (Figure 12). A higher K prior results in even a lower rate of depletion, higher B/BMSY and a lower F/FMSY (i.e. a more optimistic result for the stock status).

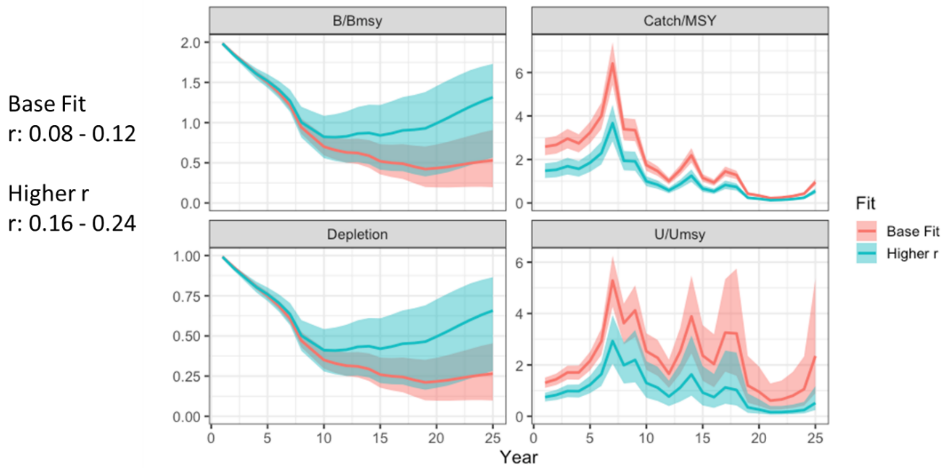


Figure 12: Effect of changes in r on the stock status parameters with changes in prior r.

Biased catch data: Changes in the time-series data (e.g. underreporting or overreporting) results in a different pattern of depletion, B/BMSY and U/UMSY (Figure 13).

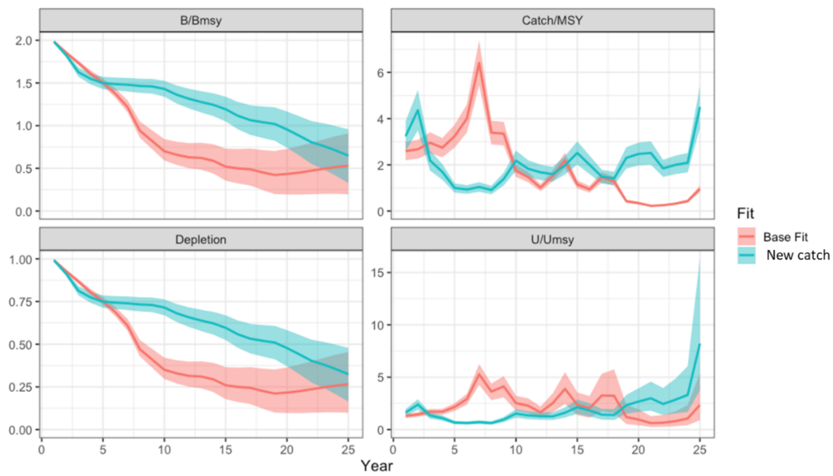


Figure 13: Effect of change in the catch series on stock status parameters.

3.2.3 Length-based methods

Fishing decreases the number of fish that survive to old age, an effect that can be seen in the size structure (e.g. fish length) of the population (Figure 14). These age and size distributions, therefore, contain information about natural mortality and recruitment.

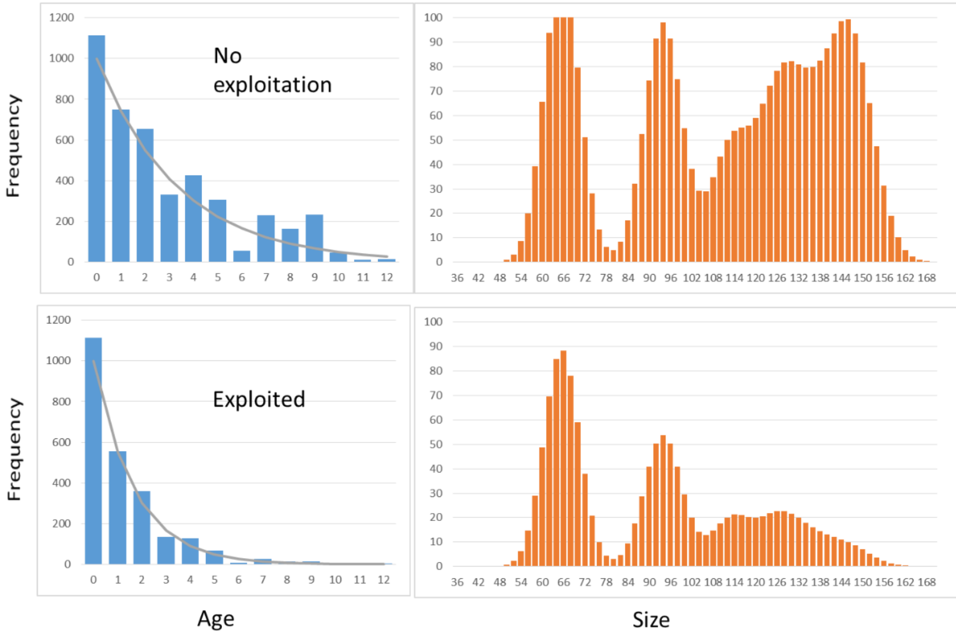


Figure 14: Example changes in the age and size distribution of an exploited and unexploited stock. *Source: Amoroso (in press).*

Length-based spawning potential ratio (LBSPR)

One of the more recent methods of analyzing length-based data is length-based spawning potential ratio (LBSPR), which estimates spawning potential ratio (SPR) from the length composition data of an exploited stock (Hordyk et al., 2015; Prince et al., 2015). The LBSPR is an equilibrium-based model that assumes that the length composition is a representative sample of the exploited population at a steady state (constant F and no recruitment variability). It also assumes that (i) somatic growth follows the von Bertalanffy growth equation, (ii) the selectivity of the fishing gear can be represented by a logistic function in the model fitting, and (iii) constant natural mortality-at-length.

The method requires the following minimum parameter inputs:

L_∞
M/k
Maturity at length:
Parameters of logistic function
L50 is length at 50% maturity
L95 is length at 95% maturity

where:

L_∞ = L infinity of the von Bertalanffy growth equation

M/k = natural mortality (M) / k of the von Bertalanffy growth equation

The model then minimizes the difference between the observed and the expected length distribution based on the input parameters (Figure 15).

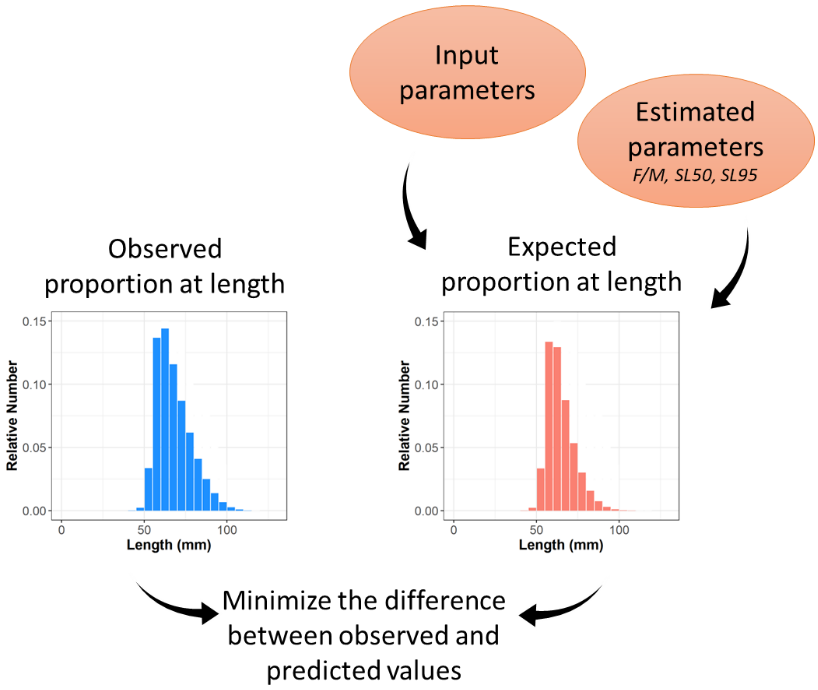


Figure 15: Fitting the LBSPR model to length-based data. *Source: Amoroso (in press)*

Uncertainties and assumptions in LBSPR

Bias in M/K: Bias in M/K produces biased estimates of F/M and SPR (Figure 16).

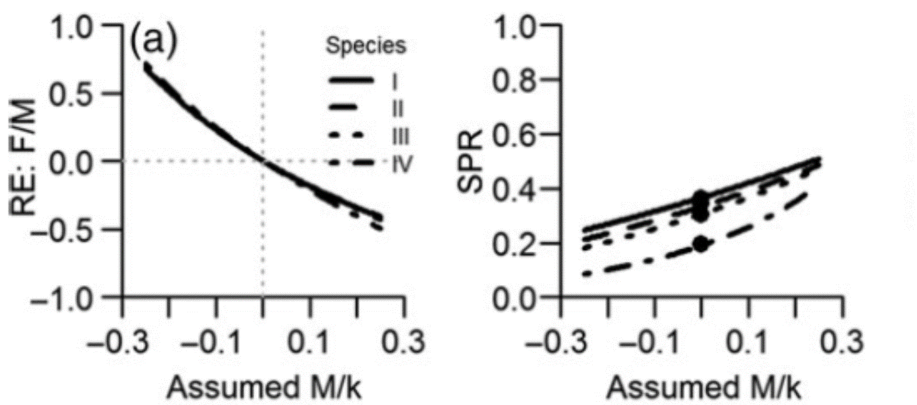


Figure 16: Effect of biases in M/k estimates on the LBSPR model outputs.

Bias in L_∞: A bias in L_∞ produces biased estimates of F/M and SPR.

Incorrect assumptions of the shape of the selectivity curve: Incorrect assumptions of the selectivity curve also produce biased estimates of F/M and SPR (Figure 17).

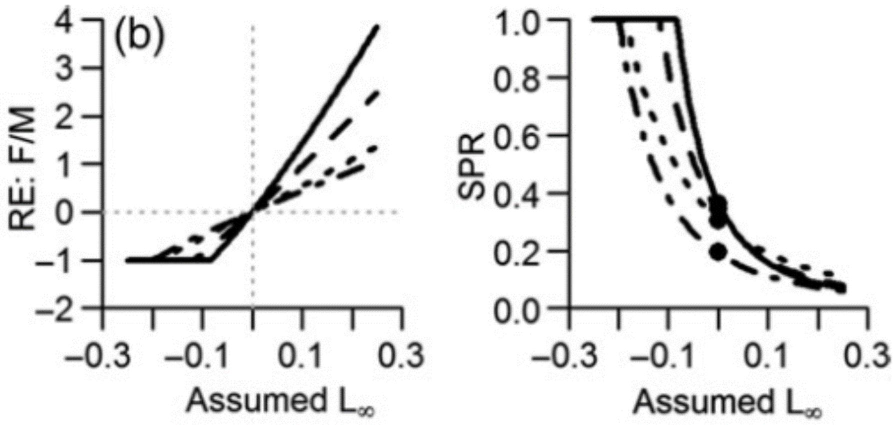


Figure 17: Effect of biases in L_∞ estimates on the LBSPR model outputs.

Incorrect assumptions of the shape of the selectivity curve: Incorrect assumptions of the selectivity curve also produce biased estimates of F/M and SPR (Figure 18).

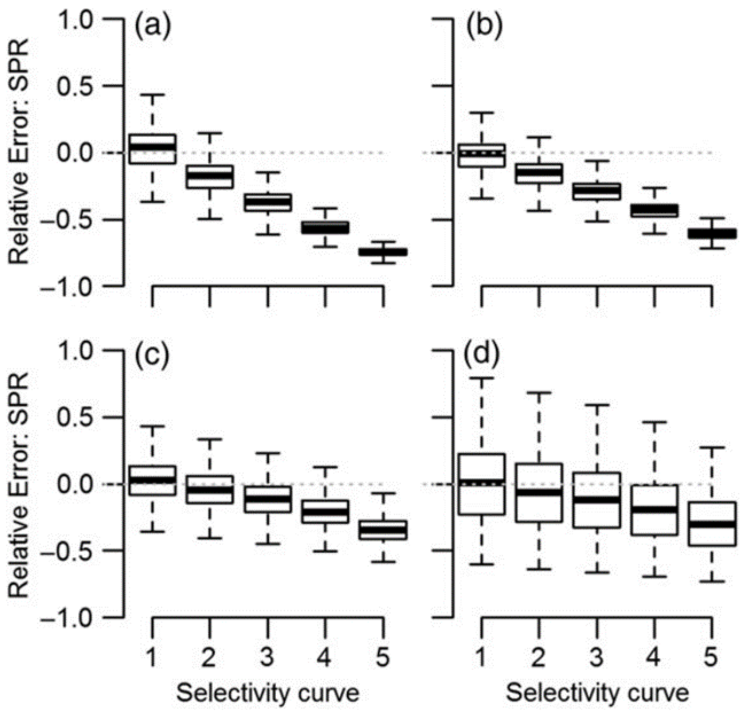


Figure 18: Effect of different assumptions about the selectivity curve on LBSPR model outputs.

4. Multi-Species Assessments

4.1. Data Needs For Multi-Species Assessments

As with single-species assessments, the assessment method is largely determined by the type of data that is available (Figure 19). These range from methods such as broad ecosystem level indicators that can be calculated based on total catch and primary production based on satellite data through to ecosystem modeling such as Ecopath with Ecosim (EwE) that need data dis-aggregated to species and geographic areas.

Useful types of information that are needed to inform an ecosystem approach for multi-species, multi-fleet fisheries include:

- System description: trophic and habitat connections
- Environmental drivers: such as productivity drivers, climate, seasonal cycles, river contributions etc.
- Human pressures: both fishing and non-fishing
- Catch composition: of the different fisheries (who catches what?)
- What affects management: this is best elucidated by looking for the most important system connections, such as fisheries interactions, or connections between predators-prey-habitat etc.
- Time series: what has changed through time in the fishery dynamics, management and catch composition?
- Trade-offs: what are the different objectives for different fisheries?

Although this appears to be a long and daunting list with huge data requirements, there are now several approaches that can help track the status of the system and possible management approaches, that does not require large datasets.

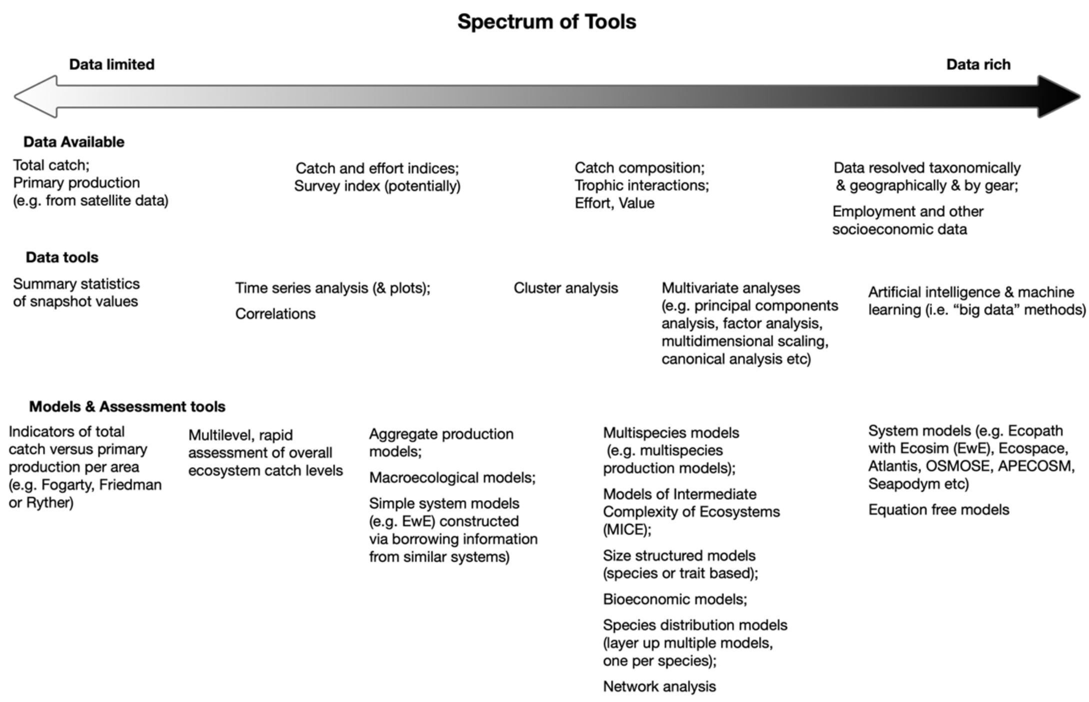


Figure 19: The range of data needed for different multi-species stock assessment methods spanning data-poor to data-rich fisheries. *Source: Leadbitter et al. (in press)*

4.2. MULTI-SPECIES ASSESSMENT OPTIONS

The main methods that can be used in the case of "data-medium" situations typical of Southeast Asia are:

1. Broad ecosystem-level indicators
2. Aggregate production models
3. Multi-species models
   3.1 Multi-species production model
   3.2 Ecopath with Ecosim (EwE)

4.2.1 Broad ecosystem-level indicators

These methods provide an acceptable total catch level based on a number of broad ecosystem indicators (see Figure 20):

- *Ryther index:* Catch per area
  Acceptable level < 1 tonne/km^2/year

- *Fogarty index:* Catch / primary production
  Acceptable level = Catch/total primary production < $1^0/_{oo}$

- Freidman index: Catch / chlorophyll
  Acceptable level = Catch/total chlorophyll < $1^0/_{oo}$

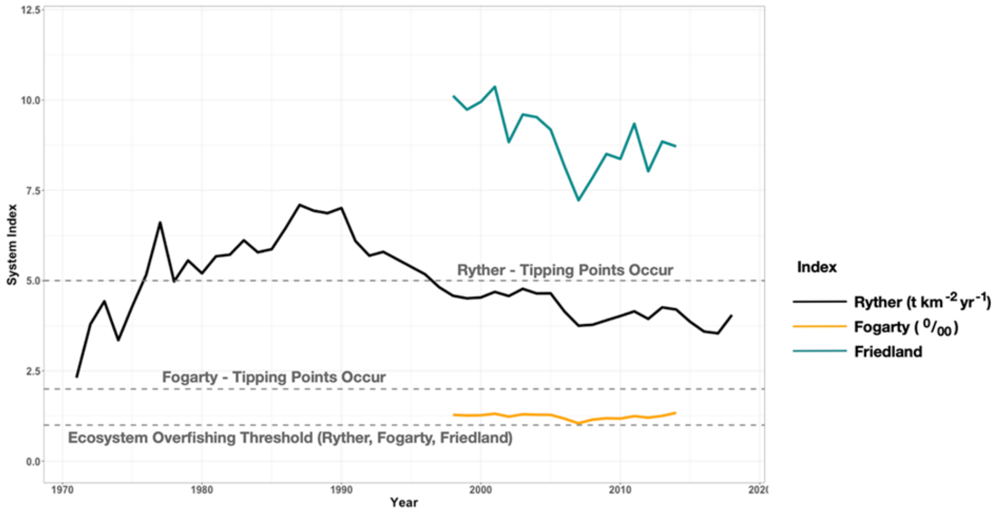


Figure 20: Broad ecosystem level indicators calculated for Thai waters of the Gulf of Thailand *Source: Leadbitter et al (in press)*

Another method is to compare the cumulative biomass with the cumulative trophic level (Libralato et al 2019). The curve highlights the loss of ecosystem integrity - when the curve is sigmoidal, this indicates that the system is unfished or lightly fished, When the curve is flattened, this indicates overfishing (Figure 21).

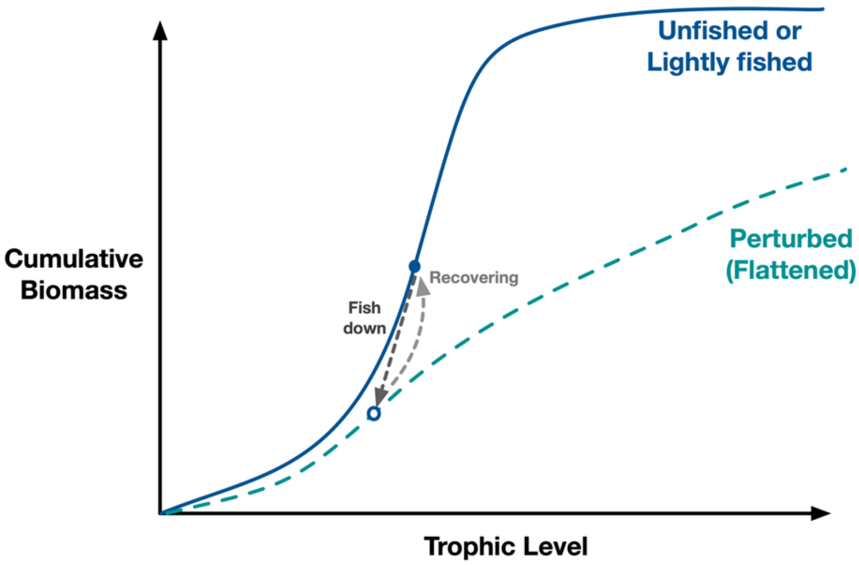


Figure 21: System structure indicator – species vs trophic level *Source: Libralato et al., 2019)*

4.2.2 Aggregate production/biomass dynamic models

Aggregate production models are a common method used to assess the status of multi-species fisheries. The method combines all the species and treats these as a "super species". The method can be applied to the fishery as a whole of a group of species with similar life-history characteristics e.g. demersal fish and pelagic fish.

The modeling is the same as that used for the single-species case where the model is fit to a time series of catch and an index of abundance (e.g. CPUE or research survey CPUEs) (Figure 22).

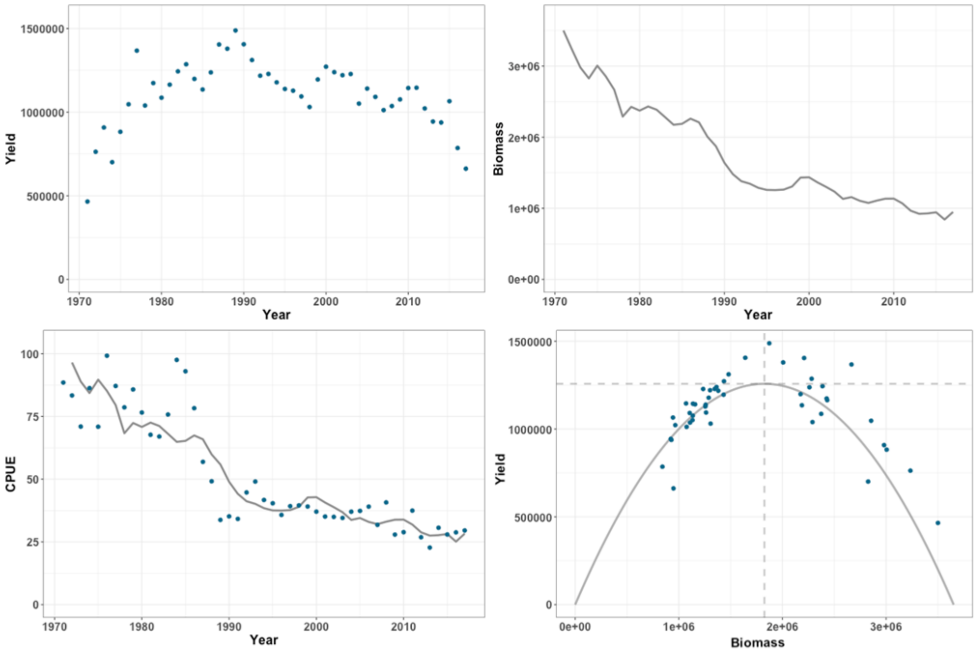


Figure 22: Example of fitting an aggregate production model to the fishery in Thai waters of the Gulf of Thailand. *Source: Leadbitter et al. (in press)*

Uncertainties and assumptions in production/biomass models

As well as the same uncertainties associated with single-species production/biomass dynamic models (e.g. biases in catch, uncertainties in the initial biomass and prior r and K values) aggregate production models are sensitive to shifts in the state of the ecosystem. As a fishery develops there is often a fish down of the more vulnerable predator species (e.g. sharks, rays, snappers) and a subsequent increase in less vulnerable species as a result of prey release (Figure 23).

This means that assessments based on an early time series of data will be different from those calculated with catch data taken later on in the time series (Figure 24). When applying the approach to time series from the Gulf of Thailand, it was found that using only the most recent decades, when the system had lost many of its largest and longest-lived species, produced MMSY estimates much higher than for time series spanning earlier years when those large species still persisted (Fulton et al., 2022). Each different period also had different levels of biodiversity, employment and profitability per unit of effort, because they represented different ecosystem states as the ecosystem changed over time.

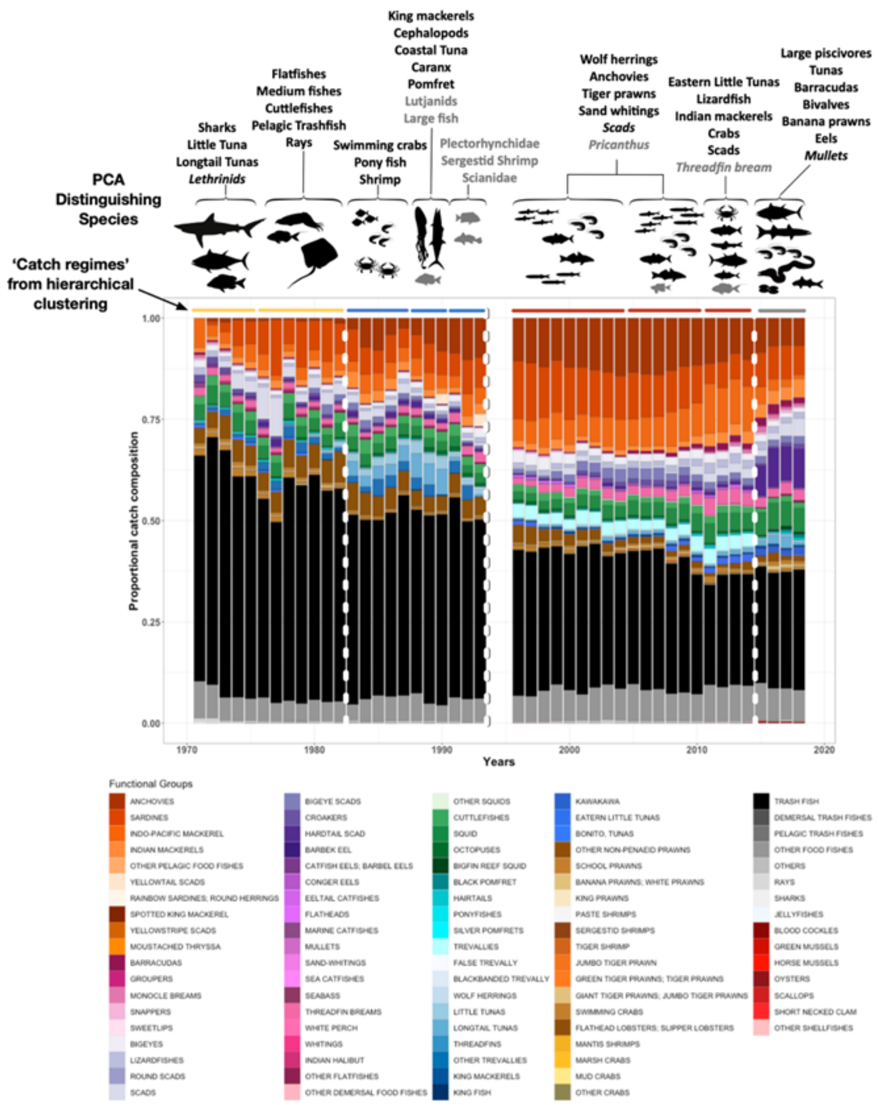


Figure 23: Changes in the ecosystem structure in Thai waters of The Gulf of Thailand. *Source: Leadbitter et al. (in press)*

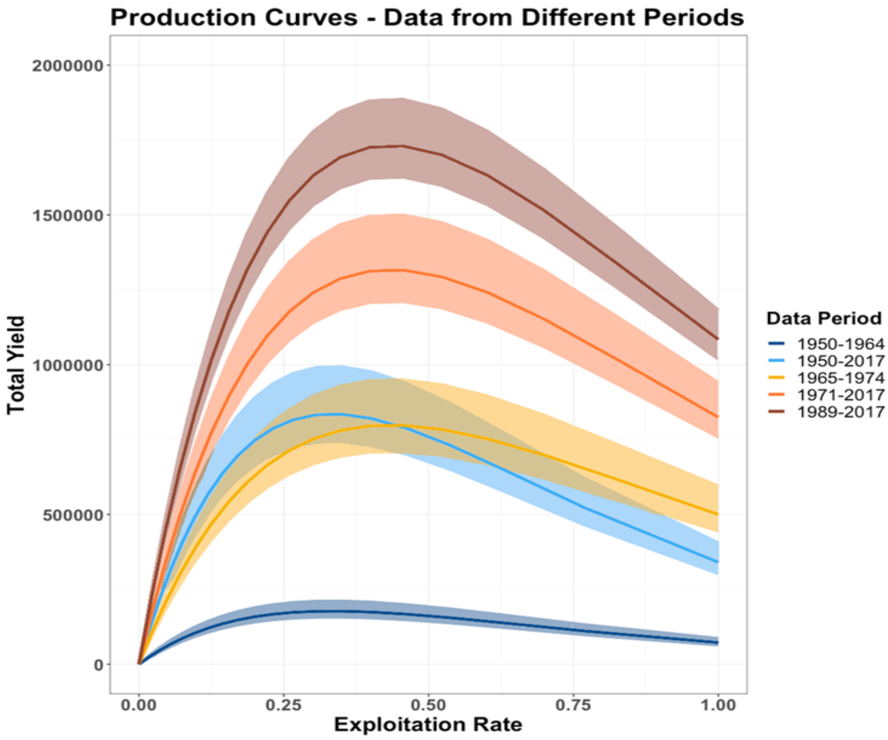


Figure 24: Production curves (and calculated MSYS) based on different time series of catch and abundance indices from Thai waters of the Gulf of Thailand. *Source: Fulton et al. 2022*

4.2.3 Multi-species models

Other available multispecies assessment models tend to resolve species or functional groups in more detail using traits (such as maximum size, habitat use etc., as in the Mizer software; Scott et al., 2014), trophic feeding relationships (e.g. Ecopath with Ecosim (EwE); Christensen and Walters, 2004), multispecies production models (e.g. Gaichas et al., 2017) or "minimum realistic" or "models of intermediate complexity" (as described in Plagányi et al., 2012) (Figure 25).

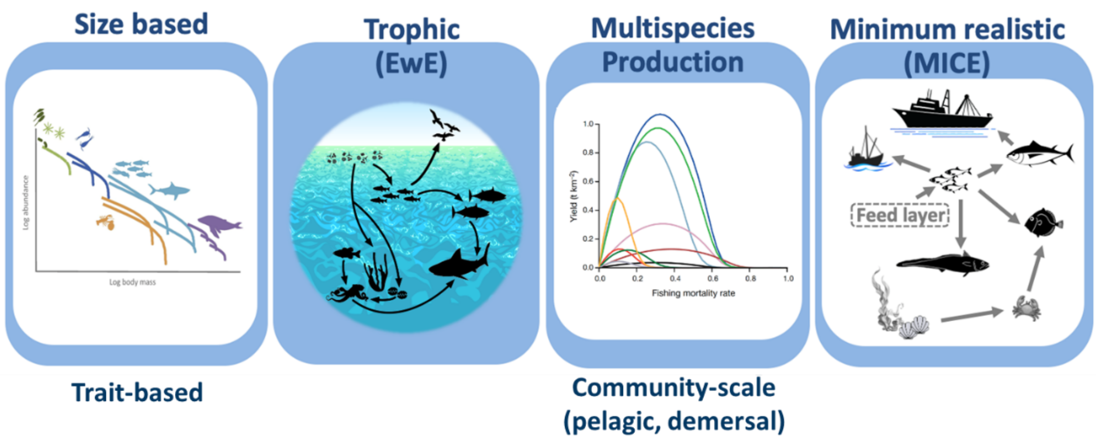


Figure 25: Different types of available multi-species assessment models. *Source: Fulton (pers com)*

The following section focuses on two of these model approaches (i) multi-species production models and (ii) EwE.

4.2.3.1 Multi-species production models

The Multispecies multi-fleet production model (MSMFPM) is an extension of the surplus production model. This model includes multiple species (or species groups) that are connected via trophic interactions between species and technical interaction between fishing fleets. The multi-fleet and multispecies version of this model has the form:

$$B_{t+1,i} = B_{t,i} + B_{t,i}\frac{r_i}{\lambda_i}\left(1 - \left(\frac{B_{t,i}}{K,i}\right)^{\lambda_i}\right) - \sum_{f=1}^{F} q_{i,f}E_f B_{t,i} - \sum_{p=1}^{P} \phi_{p,i} + \varepsilon_i \sum_{prey=1}^{PR} \phi_{i,prey}$$

where most of the parameters are as for the single species production model broken out by species *i*. For the Harvest component, the total catch of all the fleets (*f*) for species *i* is given by:

$q_{i,f}$ the catchability of the species *i* by the fleet *f*;

E_f the fishing effort of the fleet *f*, and;

$B_{t,i}$ the (exploitable) biomass of the species *i* at the time *t*;

The total predation of all the predators (*p*) on the species *i* is given by $\phi_{p,i}$ (which is the biomass in tonnes of species *i* consumed by the predator *p*) and this has the form:

$$\phi_{p,i} = \chi_p B_{t,p} \varphi_{p,i} \frac{\left(\frac{B_{t,i}}{K_i}\right)^n}{\mu_i^n + \left(\frac{B_{t,i}}{K_i}\right)^n}$$

where:

χ_p is the maximum consumption rate (y^{-1}) of the predator *p*, which indicates the rate of food that a given species can eat if their prey are infinitely available;

$B_{t,p}$ is the biomass of predator *p* at time *t*;

$\varphi_{p,i}$ is the relative preference of predator *p* for prey *i*,

μ_i describes the "half-saturation" level which is the prey biomass level at which predation consumption is half of the maximum (values from 0 to 1);

$B_{i,t}$ is the biomass of the prey *i* at time *t*;

K_i is the carrying capacity of the prey *i*, and;

n is the Holling Type exponent (e.g. *n* = 1 indicates the Holling Type II, *n* = 2 the Holling Type III.

Figure 26 shows the results of the multi-species modeling for Thai waters of the Gulf of Thailand. There are marked differences in the peak production (MSY) of the different species/species groups, with trash fish having a much higher MSY at a higher biomass.

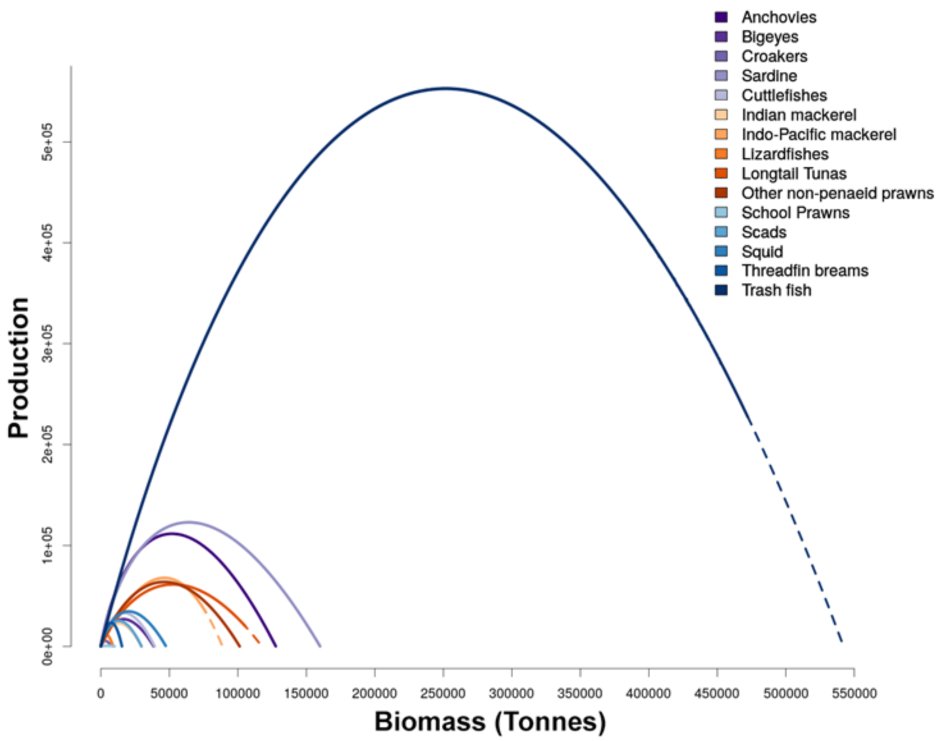


Figure 26: Production curves of the main target species-groups for the Gulf of Thailand ecosystem. *Source: Leadbitter et al. (in press)*

After the model has been fitted, there are many useful ways to use the output. One common approach is to look at predictions of future status of the fishery resource under different management intervention scenarios (Figure 27).

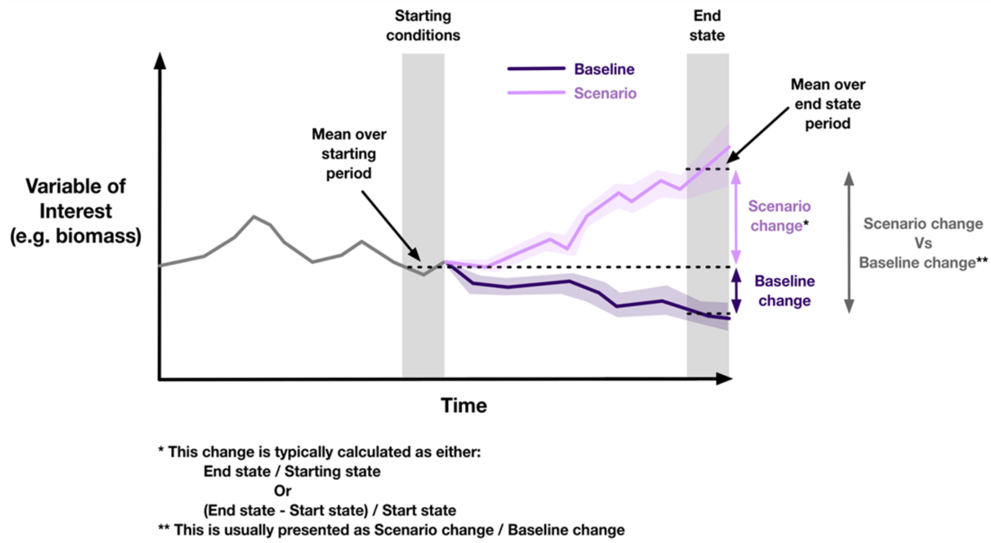


Figure 27: Using a multi-species model to predict future fishery status based on different future scenarios. *Source: Leadbitter et al. (in press)*

As an example, the multi-species production model was used to examine likely responses to changes in fishing effort in Thai waters of the GoT. The scenarios were:

- Reducing the effort of all fishing gears by 20%
- Reducing the fishing pressure of all fishing gears by 30%
- Reducing the effort of pair trawlers by 50%
- Increasing the effort of pair trawlers x2

Most scenarios resulted in an increase in the production of the main surimi/market species (Figure 28), in particular anchovies and threadfin bream.

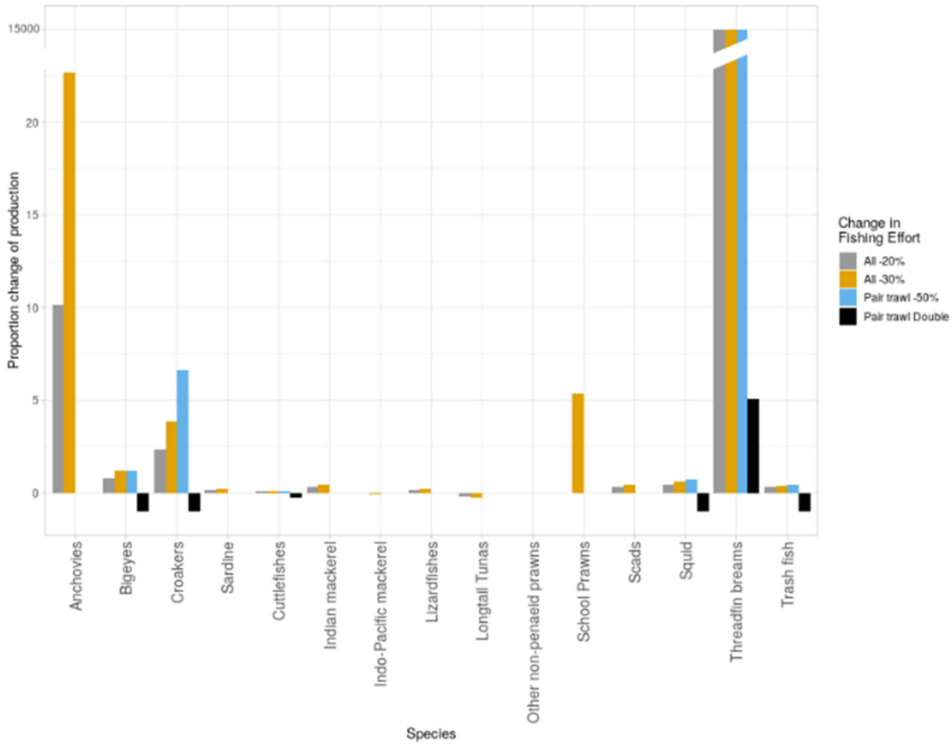


Figure 28: Proportional changes in production biomass under different scenarios of fishing effort. *Source: Leadbitter et al (in press)*

Uncertainties and assumptions in multi-species production models

All the same uncertainties associated with multi-species aggregate production/biomass dynamic models (e.g. biases in catch, uncertainties in the initial biomass and prior r and K values) apply to multi-species production models plus assumptions about predator-prey relationships.

4.2.3.2 Ecopath with Ecosim (EwE)

Ecopath with Ecosim (EwE) is the probably the best known of all marine ecosystem modeling approaches and has been applied to many marine ecosystems across the world. The software includes three model components:

- Ecopath: a static mass-balance model for considering a snapshot of biomass or energy flow through a foodweb
- Ecosim: which takes the Ecopath state and projects it forward through time under scenarios of fishing pressure and primary production forcing
- Ecospace: a grid-based implementation of Ecosim, which can include movement and differential availability of habitat and spatially resolved fishing pressure.

The EwE approach can be used to provide information for a number of different types of problems – such as the food web effects of fishing, strategic fisheries management at the ecosystem level, estimation of reference points and ecological indicators, invasive species, climate change and even the effects of pollution. EwE models are usually based on species/species group information, although in some cases simple age structure (in the form of life stages are included).

Each species group included in the model is represented as a biomass pool. The core assumption of the is that food consumed becomes production (consisting of respiration, predation, fishing yield, net migration, unassimilated materials (waste) and other sources of mortality). This gives the Ecopath fundamental equation for the biomass dynamics of species *i* as:

$$\left(\frac{P}{B}\right)_i \bullet B_i = \sum_j^n \left(\frac{Q}{B}\right)_j \bullet B_j \bullet DC_{i,j} + E_i + Y_i + BA_i + \left(\frac{P}{B}\right)_i \bullet B_i \bullet \left(1 - EE_i\right)$$

where B_i is the biomass of species *i*, P_i is production (and *P*/B equates to total mortality), Q_i is consumption, DC_i is the diet composition (the fraction of the diet of predator *j* made up of species *i*), BA_i is biomass accumulation (e.g. due to a recovery trend), E_i is net migration, and EE_i is the proportion of production used in the system (known as ecotrophic efficiency). This means that any unmodeled mortality is represented by the term (1- EE_i).

The base data needed for the model is the diet composition, landings (and discards if available) and the species group parameters – *B*, *P/B*, *Q/B*, assimilation rate and EE (any one of these can be omitted per group, typically EE, with the others used to solve for that missing parameter using a set of simultaneous equations).

In many cases, the model can be modified from existing models of similar ecosystems, and it is often not necessary to start from scratch. Existing models can be found at http://ecobase.ecopath.org/. For example, existing models already exist for the Thai waters of the Gulf of Thailand and Southwest Viet Nam.

After the model has been fitted alternative management scenarios – such as reduction or increase in effort per fleet (gear type) or changes in primary production can be explored. Again as an example, we use the changes in biomass of major species groups in the Thai waters of the GoT. The scenarios were:

- Reducing the fishing pressure of all fishing gears by 30%
- Reducing the effort of pair trawlers by 50%
- Full change of the effort reduction
- Only partial changes in effort reduction.

In this case, a large proportion of the productive prey groups change biomass by < 10%. However, the market and larger bodied fish all benefit – most by < 25% increase, but some by as much as 75% increase. In contrast, the various medium sized demersal fish groups and sharks decline in biomass by 10-25%

(due to changes in prey, competitor and predator abundance). These shifts in biomass combine with the drop in effort to see an overall catch decline by approximately 33%, but value declines by only 25% (Figure 29).

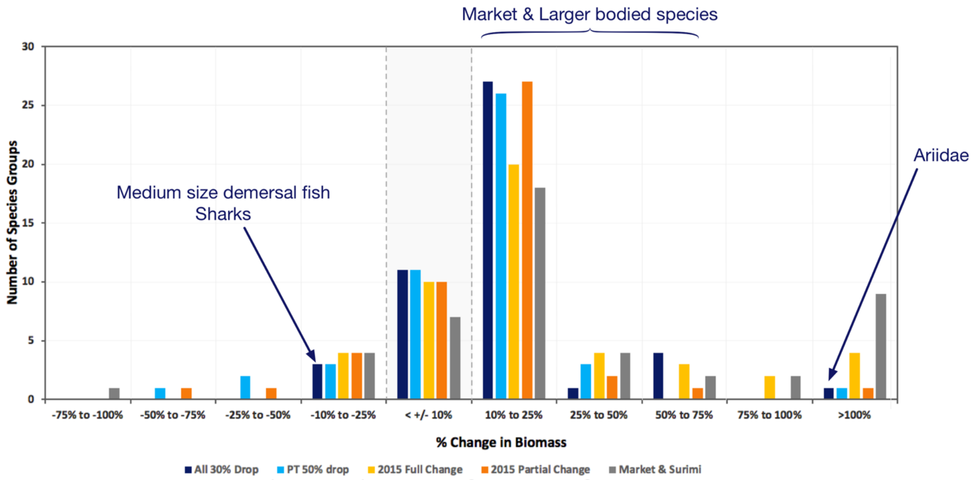


Figure 29: Changes in the biomass as a result of alternative fishing scenarios in the EwE Gulf of Thailand model. The arrows show the results of the “all gears decreased by 30%” scenario. *Source: Leadbitter et al. (in press)*

A particularly useful Ecosim tool is the Fishing policy search which runs an optimization to find what mix of relative effort across the different gears maximizes a set of user defined objectives (you define the relative weight of economic, social and environmental objectives and then try searches from at least ten starting points to find the effort mix that achieves those objectives). An example for the GoT model is shown in Figure 30. This shows the differences in achieving the MMSY (1.5 million tonnes (yellow dot)) that occurs around 70% of the fishing effort in 2015. The yields providing maximum economic return and robust ecosystem structure differ significantly from this point (1.2 million tonnes (red dot) and 1.1 million tonnes (green dot), respectively). The maximum social objective of maximum employment occurs around 1.4 million tonnes (blue dot), but this higher yield is based on an ecosystem that has ecosystem structures that are degraded, with many extirpated species, which is not robust to environmental shocks and can show quite large inter-annual variation. These features are undesirable for achieving ecosystem states that are reliably sustainable in the long-term. The lower yield levels (red and green dots) are much more robust, but will not support as much short-term employment.

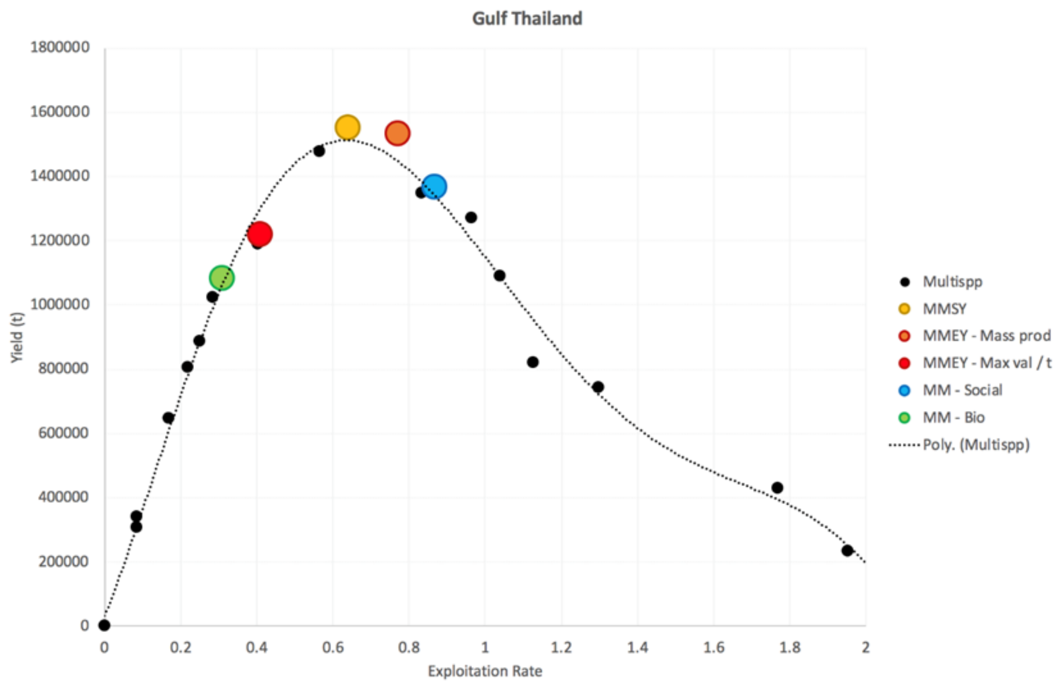


Figure 30: A yield curve generated by running the EwE policy search for Gulf of Thailand under different objective weightings. The coloured dots mark particular optimization outcomes: *MMSY* is maximum multispecies yield (maximal food security); *MMEY – Max value/tonne (val/t)* is maximum multispecies economic yield that is equivalent to classical definition of MEY for classical single species theory); *MM - Social* is the point where maximal employment of fishers and their immediate supply chain contacts exists; *MM - Bio* is the point where environmental objectives of rebuilding and maintenance of a robust ecosystem structure is met. *Source: Leadbitter et al. (in press)*

5. Single-Species or Multi-Species Assessments?

Given that we can carry out both single-species and multi-species assessments, it is pertinent to ask "which is better"? The answer is that both are needed. Single-species by themselves have a number of issues (see section below) that need to be considered, while multi-species assessments provide a better overview of the fishery, details about individual species can be lost. A combination of multi-species assessments and single-species assessments of a set indicator species is recommended.

5.1 Interpreting Single-Species Assessments in a Multi-Species Fishery

The three issues that need to be considered when interpreting single-species stock assessments in a multi-species fishery are:

1. The sum of the individual stocks maximum sustainable yield (MSYs) is greater than the aggregate multi-species MSY (MMSY).
2. In a multi-species fishery fished at MMSY, some stocks will be below their MSY, some at or around MSY and some above MSY.
3. Just considering the status of a small number of common species results in a biased view of the status of a multi-species fishery.

5.1.1 The sum of the individual stocks MSYs is greater than the aggregate multi-species MSY (MMSY)

As shown in Figure 31, each individual stock has its own relationship between fishing effort and catch. Because of food-web interactions the MMSY is not the sum of the individual MSYs.

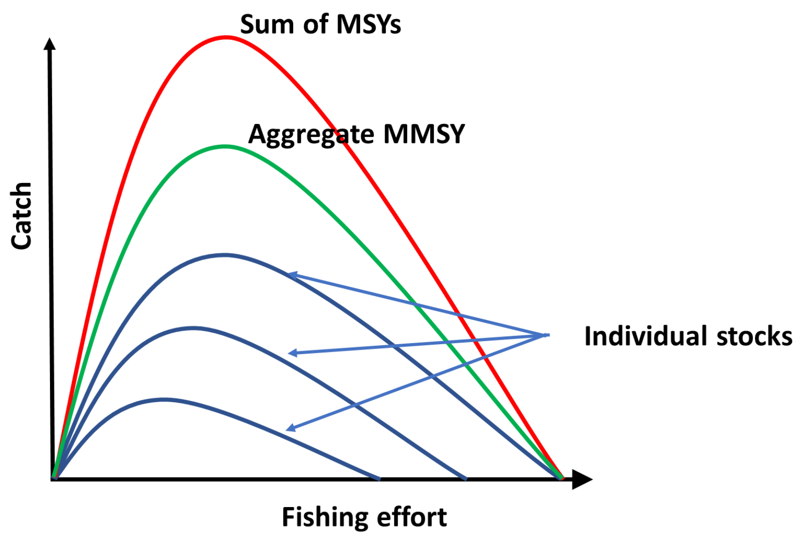


Figure 31: Relationship between catch and fishing effort of three individual stocks. The sum of the MSY curves is shown in red, while the aggregate MMSY fit of the stocks is shown in green.

5.1.2 In a multi-species fishery fished at MMSY, some stocks will be below their MSY, some at or around MSY and some above MSY

The MSY for individual stocks occurs at different fishing effort levels relative to the MMSY, it is not possible, or in fact, desirable to have all stocks fished at MSY. To ensure that all stocks in a multi-species fishery were fished at a level below their MSY would require such a low fishing effort that the fishery would be uneconomic and considerable amounts of the commercial stock would be greatly underfished.

Figure 32 demonstrates the relationship between fishing effort and catch for several stocks, each of which have their own MSYs. The more vulnerable stocks (e.g. sharks, rays, snapper) will have a MSY well below the aggregate MMSY, while the less vulnerable stocks will have MSYs above the aggregate MMSY. When the total fishery is being fished at MMSY, the more vulnerable/high-risk stocks are more likely to be fished at levels greater than their MSY and the less vulnerable/ low-risk stocks fished at levels less than their MSY.

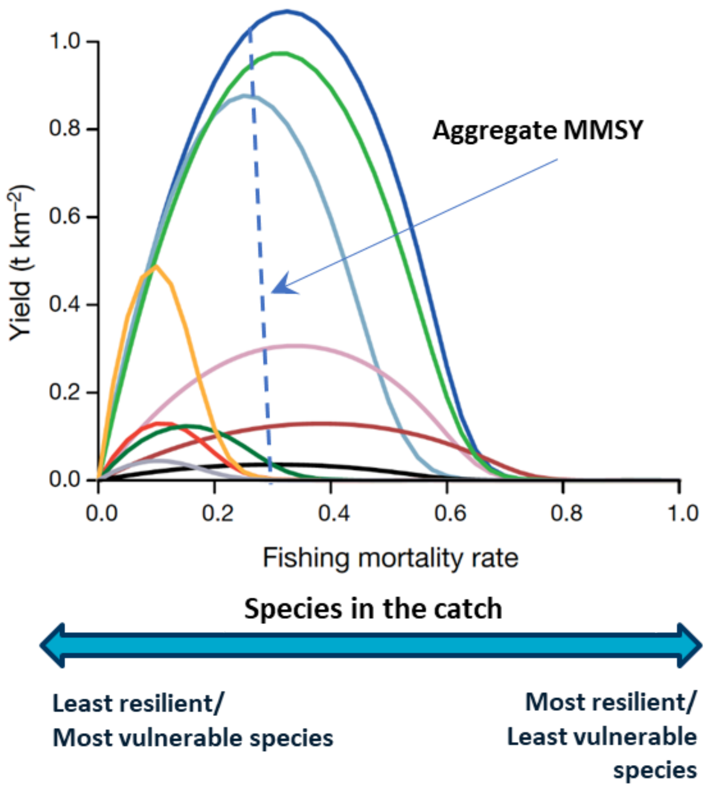


Figure 32: Yield curves for several individual stocks with different values of their MSY shown against the aggregate MMSY for all stocks. *Source: Newman et al. 2018*

5.1.3. Focussing assessments on a small number of commonly-fished stocks will result in a biased understanding of the status of a multi-species fishery

Figure 33 shows the status of a number of species/species groups from the GoT in 2020. The less resilient stocks (e.g. sharks, rays, snapper, catfish and sweetlips) tend to be more overfished than the less vulnerable stocks (e.g. Indian mackerel, swimming crabs and lizardfish).

Confining the analysis of the status of a multispecies fishery to only a few species (especially if they are all from the same risk group) will result in a very different conclusion on the overall status of the fishery. In this example of 19 stocks, if Indian mackerel, lizardfish and swimming crabs were selected as representative of the fishery and assessed using single-species assessment methods it would be concluded that the fishery is sustainably fished. However, when a more complete selection of species in medium and higher risk groups is used, the picture is quite different (Figure 33).

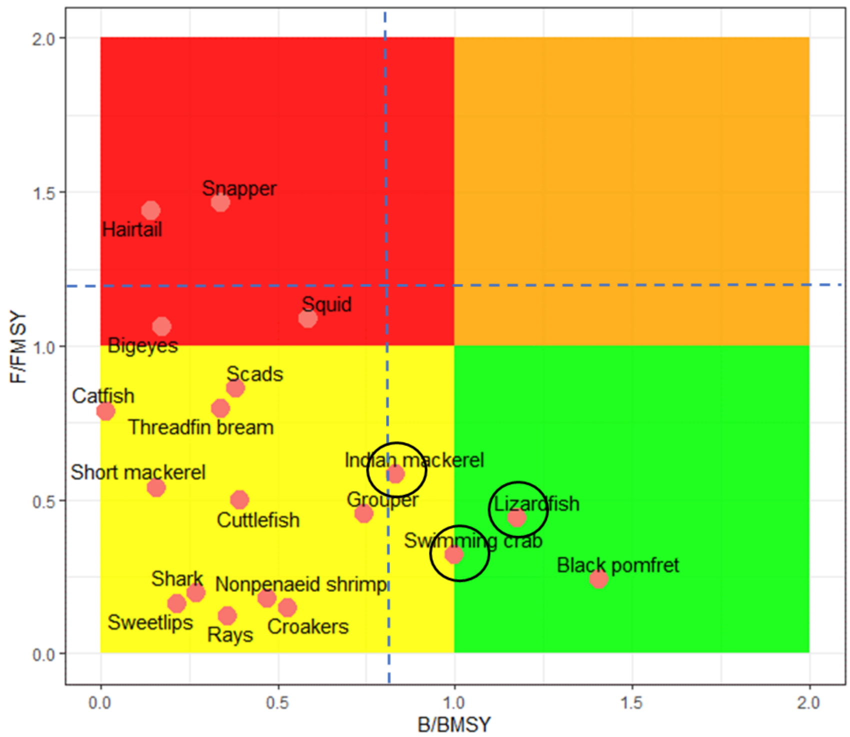


Figure 33: Status of the 19 case-study stocks in 2020. The circled stocks show that selecting common species for single-species assessment could result in a wrong assessment of the status of the fishery as a whole. *Source: Staples et al. (in press).*

5.2 Combining Multi-Species Assessments and Single-Species Assessments

To be able to correctly interpret single-species assessments as part of multi-species fishery, a combination of multi-species assessments with single-species assessments for a set of indicator species is recommended:

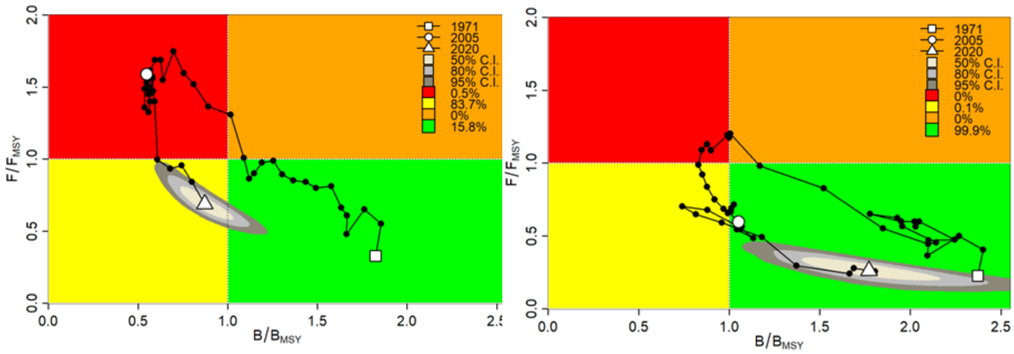
1. Multi-species assessments to give a picture of the overall state of a fishery, and;

2. Single-species assessments for indicator species from different risk groups to reduce the total number of assessments required but still give an objective overview of the fishery.

5.2.1 Multi-species stock assessments

As an example, an aggregated production model was fitted to the demersal trawl fishery data of the Thai waters of the GoT based on catch records and research vessels abundance indices from 1971 -2020 (Figure 34). The analysis shows that the trawl fishery as a whole is overfished but has not been subjected to overfishing in recent years (since 2016 when management reforms were introduced). Further analysis shows that it is the surimi and market fish that are overfished (bottom left and right plots), with trash fish being underfished and subjected to underfishing (right hand top plot). Depending on the objective of management, the assessment is important to guide future management decisions. For example, the analysis indicates that it is the catches of both surimi and market fish that need to be controlled, not trash fish (e.g. through effort limitation of trawlers). Trash fish could withstand further fishing effort, but at the expense of higher value surimi and market fish.

TOTAL TRAWL FISHERY TRASH FISH



SURIMI FISH MARKET FISH

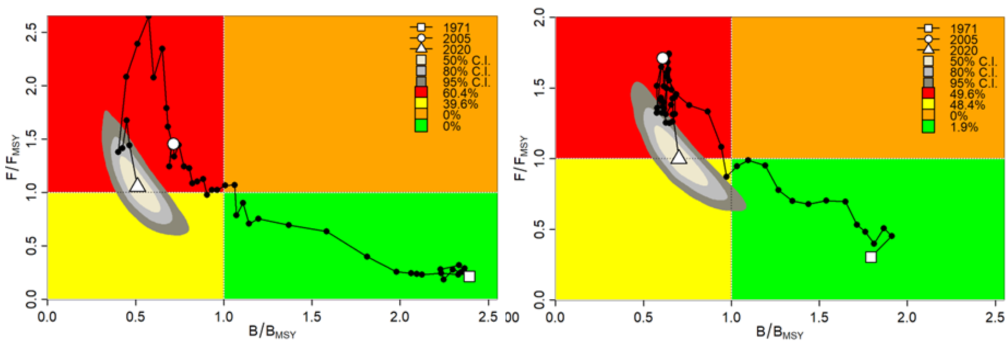


Figure 34: Kobe plots for the demersal trawl fishery in Thai waters of the Gulf of Thailand and its three main components – trash, surimi and market fish. Source: Staples et al. (in press)

5.2.2 Indicator species approach with a focus on limit reference points (e.g. BLIM)

Assessments for single species can be added through an indicator species approach. This approach is a way to choose what is monitored and analyzed to help focus on the linkage between fishery status and management response. The first step is to select indicator species based on PSA/vulnerability scores and importance for management (management determining species).

It is important that the selected indicator species have ongoing assessments and there is a need to identify the ongoing assessment methods and ensure adequate monitoring. It is useful to select three groups of species based their vulnerability:

- Likely 'overfished' high-risk/vulnerability species
- Likely 'sustainably fished' medium-risk/vulnerability species
- Likely 'underfished' low-risk/vulnerability species (high resilience)

Table 1 shows an example of selecting indicator species based on the criteria of (i) inherent vulnerability, (ii) current risk, (iii) management importance.

Table 1: An example of selecting indicator species based on the criteria of (i) Inherent vulnerability, (ii) current risk, and (iii) management importance.

Species chosen for assessment by population model	Species	Inherent vulnerability	Current risk	Management importance	Combined
***	Species 1	4	4	5	80
***	Species 2	4	3	5	60
***	Species 3	3	2	3	18
***	Species 4	3	2	2	12
***	Species 5	3	3	4	36
	Species 6	2	2	2	8

Source: Modified from Newman et al. (2018)

Management importance in this regard also includes selecting species that are high-risk and more vulnerable to fishing. Under the UN convention on the Law of the Sea (UNCLOS), all species belonging to the same ecosystem need to be maintained above levels at which their reproduction may become seriously threatened, that is the Point of Recruitment Impairment (PRI). A common reference point for the PRI is the biomass limit (BLIM) often defined as 20 percent of the virgin biomass (biomass before fishing started).

The use of indicator species and the BLIM threshold is important when managing a fishery for MMSY because there will be some stocks that are overfished under the MMSY scenario and it is important that these stocks be maintained above the 20 percent BLIM threshold. If the vulnerable stocks fall below this level, then it is not possible to claim that the fishery managed at MMSY is sustainably managed.

Using the case-study stocks as example indicator species for the Gulf of Thailand trawl fishery, (Table 2) only 6 of the 19 case-study stocks were above 20 percent BLIM in 2020 (i.e. B/K, where B = biomass and K = carrying capacity).

Table 2: Status of the 19 case-study stocks in relation to a BLIM of 20%.

Risk grouping	Species/group	B/K
High risk	Snapper	Below BLIM (<20%)
	Sea catfish	Below BLIM (<10%)
	Sharks	Below BLIM (<20%)
	Rays	Below BLIM (<20%)
	Sweetlips	Below BLIM (<10%)
	Croakers	Below BLIM (<20%)
	Scads	Below BLIM (<20%)
Medium risk	Bigeyes	Below BLIM (<20%)
	Threadfin bream	Below BLIM (<20%)
	Black pomfret	Above BLIM (>20%)
	Grouper	Below BLIM (<20%)
	Largehead hairtail	Below BLIM (<10%)
	Indian mackerel	Above BLIM (>20%)
	Short mackerel	Below BLIM (<10%)
Low risk	Lizardfish	Above BLIM (>20%)
	Swimming crabs	Above BLIM (>20%)
	Cuttlefish	Below BLIM (<20%)
	Non-penaeid shrimp	Above BLIM (>20%)
	Squid	Above BLIM (>20%)

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Appendix A: Software Packages for some Common Stock Assessment Methods

Production/biomass dynamic models

Production/biomass dynamic models estimate changes in biomass as a function of the biomass of the preceding year, the surplus production of biomass in a given year, and the removal by the fishery in the form of catch. In these, somatic growth, reproduction, natural mortality, and associated density-dependent processes are captured in the interplay of two major parameters - the intrinsic rate of population increase (r) and the carrying capacity (K).

Two r packages, which fit the data using a Bayesian model where the probability to represent all uncertainty within the model are used are listed below. The fit includes both the uncertainty in both the input and output. The model fit starts with informed values (called priors) and fits the data to the model to provide estimates of the parameters (called posteriors).

Sraplus

The sraplus package requires a time-series of catches, a time-series of abundance indices, and an estimate of initial biomass, as well as a prior for r and K.

The sraplus package can be installed from github (https://github.com/)

```
# MuLTISPECIES sraplus

#--------------------------------------------------------

#Packages

#--------------------------------------------------------

install.packages("devtools")

devtools::find_rtools()

devtools::install_github("danovando/sraplus")
```

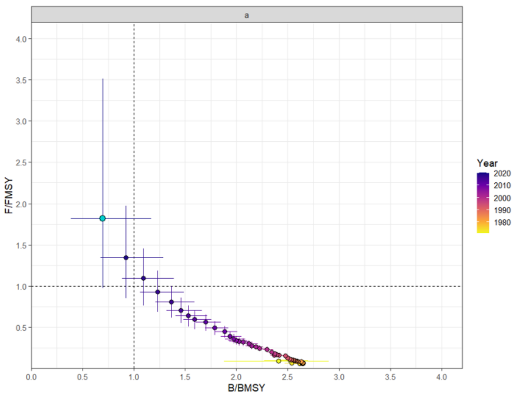
A full account of running the R package is at https://danovando.github.io/sraplus/

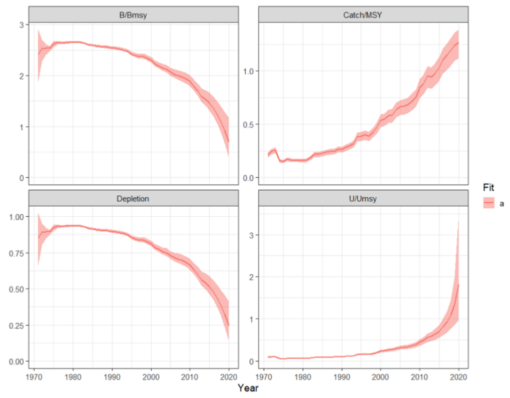
Example output for Southeast Viet Nam total fishery:

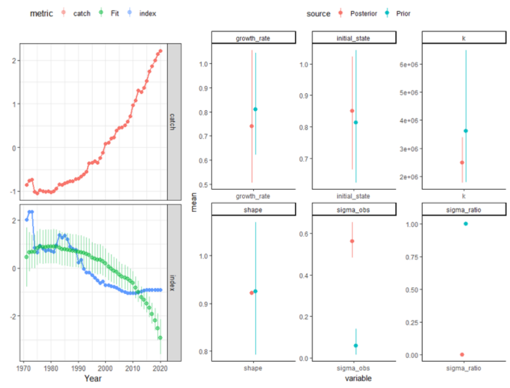
variable	mean	sd	lower	upper
bmsy	880416	173285	626072	1192205
k	2494097	490892	1773575	3377351
msy	677395	49970	616538	765327
r	0.740	0.172	0.507	1.050
umsy	0.803	0.186	0.550	1.140

variable	year	mean	sd	lower	upper
B/BMSY	2020	0.698	0.346	0.387	1.17
C/MSY	2020	1.27	0.0706	1.12	1.39
B/K	2020	0.246	0.346	0.137	0.414
F/FMSY	2020	1.82	0.403	0.972	3.51

Example plots for Southeast Viet Nam fishery







Jabba

The JABBA package requires a time-series of catches, a time-series of abundance indices, and an estimate of initial biomass, as well as a prior for r.

Before installing JABBA, you need to install JAGS

https://sourceforge.net/projects/mcmc-jags/files/

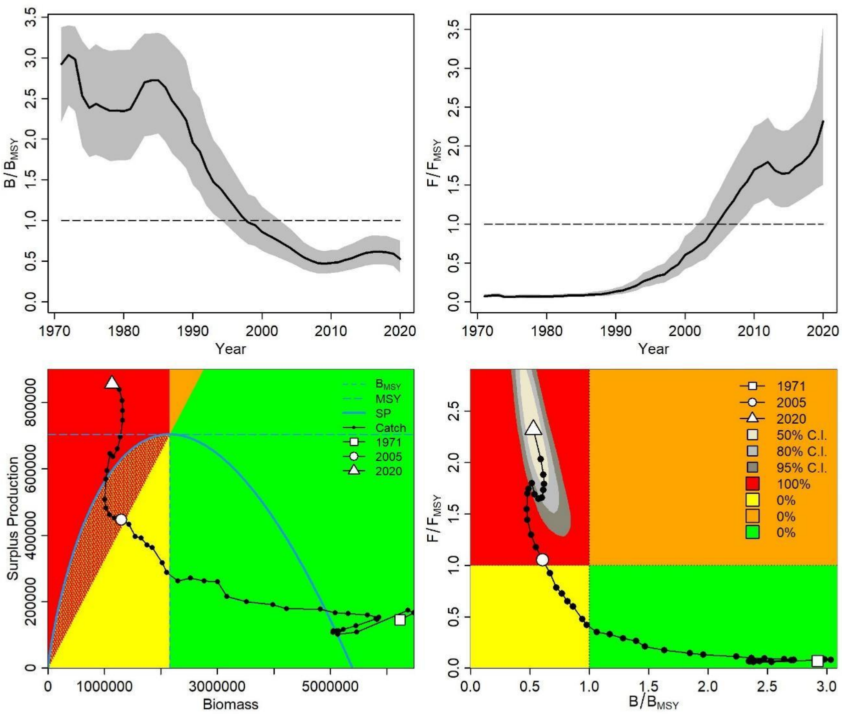
The JABBA package can then be installed from github (https://github.com/)

Full details of how to run JABBA are at https://github.com/jabbamodel/JABBA

Example output for Southeast Viet Nam fishery:

	mu	lci	uci
K	5,391,477	3,828,647	7,836,677
r	0.388	0.286	0.523
psi	0.978	0.725	1.294
sigma.proc	0.182	0.14	0.208
m	1.188	1.188	1.188
Hmsy	0.327	0.241	0.44
SBmsy	2,156,492	1,531,389	3,134,528
MSY	701,779	586,030	868,387
bmsyk	0.4	0.4	0.4
P1971	1.169	0.887	1.352
P2020	0.21	0.143	0.302
B_Bmsy.cur	0.526	0.359	0.756
H_Hmsy.cur	2.321	1.501	3.553

Example plots for Southeast Vietnam:



LBSPR

The LBSPR package is now available on CRAN:

```
install.packages("LBSPR")
```

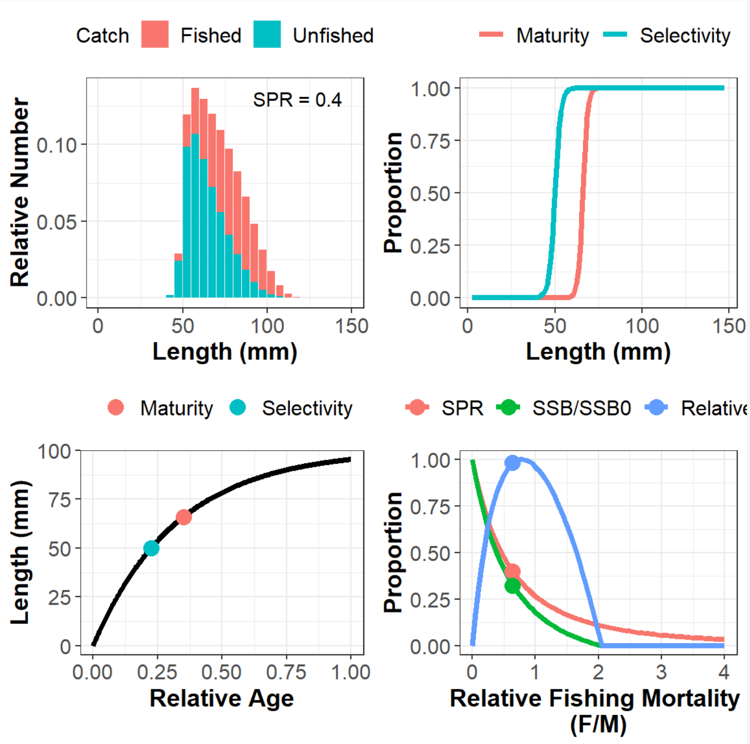
You can also install the development version of the package from GitHub using the devtools package:

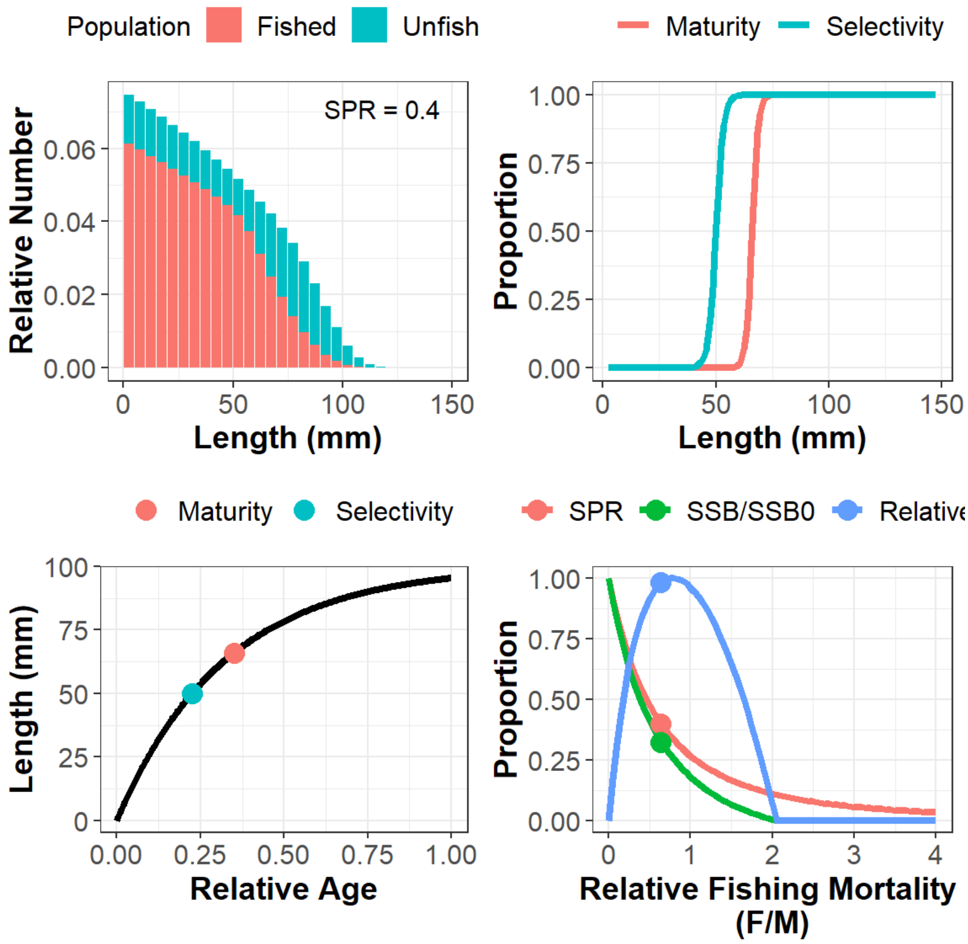
```
install.packages("devtools")

devtools::install_github("AdrianHordyk/LBSPR")
```

Full details for running the package is at

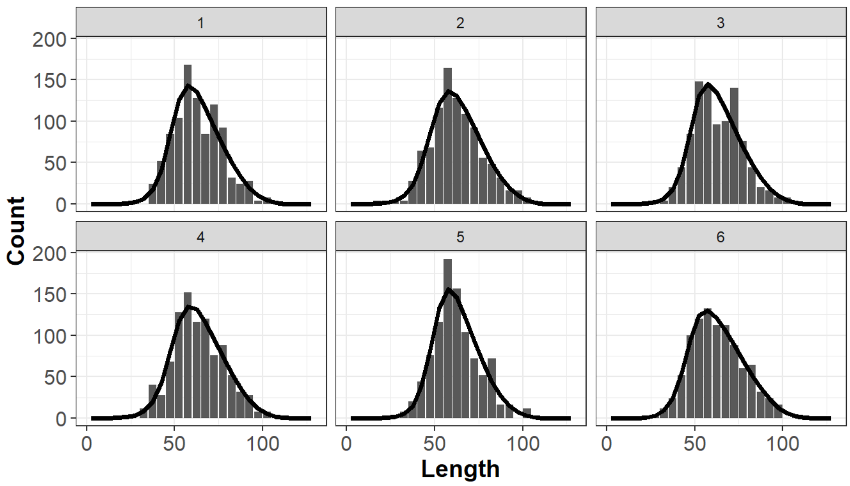
https://cran.r-project.org/web/packages/LBSPR/vignettes/LBSPR.html

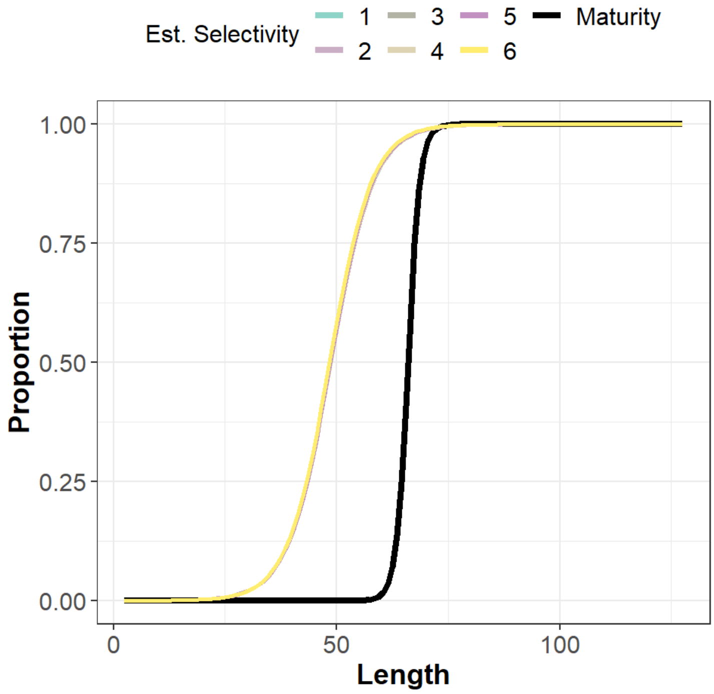
Example plots for the simulation

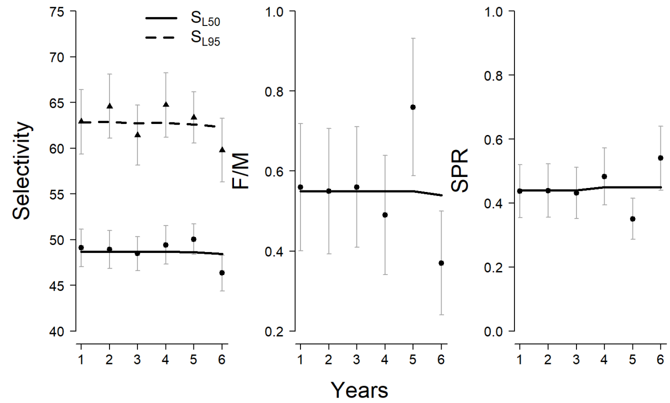




Example plots for fitting the length data




Est. Selectivity
1
2
3
4
5
6
Maturity
Proportion
1.00
0.75
0.50
0.25
0.00
0
50
100
Length


S_{L50}
S_{L95}
Selectivity
F/M
SPR
Years

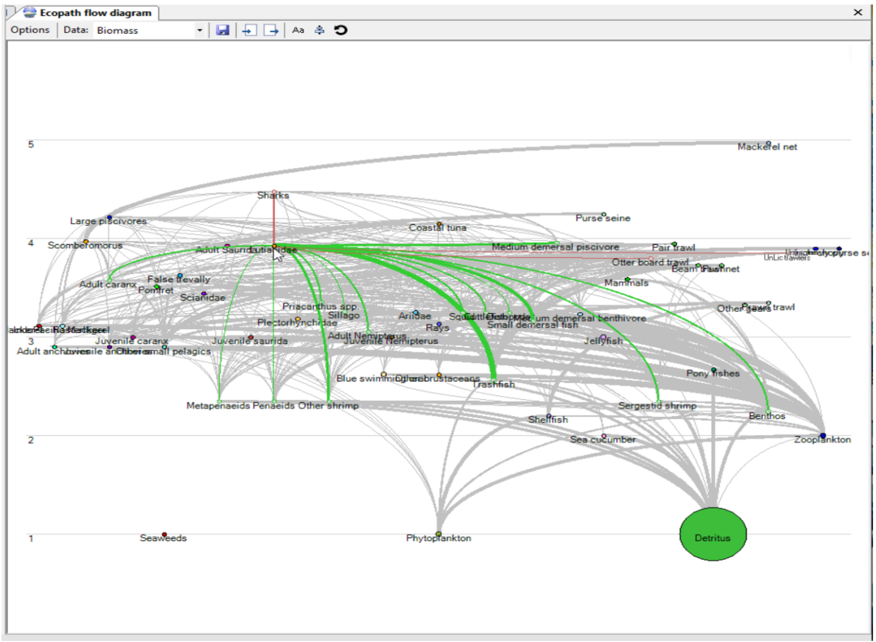
Ecopath with ecosim

The software and documentation are available from https://ecopath.org/.

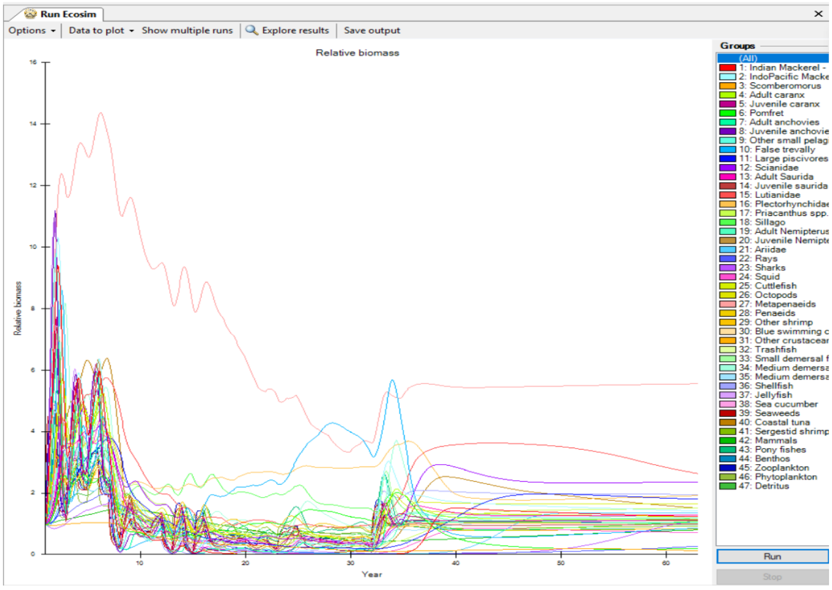
Full details for developing and running the model is at https://www.researchgate.net/publication/267193103_Ecopath_with_Ecosim_A_User's_Guide

and Leadbitter et al. (in press)

Once the model, a balanced Ecopath model has been developed and tested, the Output tools built into EwE can be used to investigate ecosystem structure and flows, as well as the size and value of fisheries.



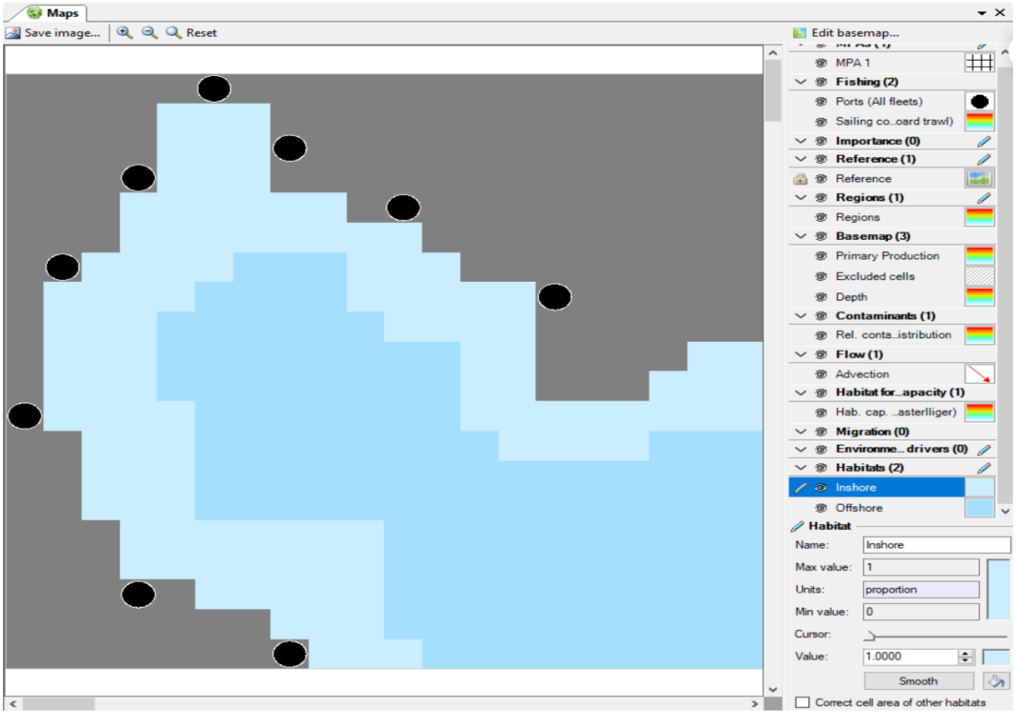
Then you can move to the time dynamic Ecosim model.



This then allows the examination of alternative management scenarios – such as reduction or increase in effort per fleet (gear type) or changes in primary production can be explored. To change the amount of effort in a scenario enter this via the Fishing effort page – for instance at the end of the historical time series reduce effort and project forward (see below). The idea is to mimic the process followed in reality, that is why it is important to start the change at the end of the historical time series so that the system is undergoing the same kind of changes happening in the real world.

It is then possible to set up scenarios to look at the effect of alternative management interventions and explore fisheries policy information, as described on Page 24 and 25 above.

It is also possible to take this model into a spatial version (**Ecospace**) by applying it to a map of the system, including the location of major ports and habitats (e.g. reefs or shallow vs deeper water.


Maps
Save image...
Reset
Edit basemap...
MPA 1
Fishing (2)
Ports (All fleets)
Sailing co..oard trawl)
Importance (0)
Reference (1)
Reference
Regions (1)
Regions
Basemap (3)
Primary Production
Excluded cells
Depth
Contaminants (1)
Rel. conta..istribution
Flow (1)
Advection
Habitat for..apacity (1)
Hab. cap. ..asterlliger)
Migration (0)
Environme...drivers (0)
Habitats (2)
Inshore
Offshore
Habitat
Name:
Inshore
Max value:
1
Units:
proportion
Min value:
0
Cursor:
Value:
1.0000
Smooth
Correct cell area of other habitats