INTRODUCTION

Fisheries science is the multidisciplinary study of fisheries. Which disciplines are part of fisheries science is to a point a matter of opinion, but a preliminary list would include fisheries biology, marine ecology, stock assessment, natural resource economics, social sciences, fishing technology, oceanography, statistics, and computer modeling.

A fishery is defined as the set composed of a particular stock plus the fishing activities related to its harvest, inclusive of fishermen, vessels, gears and even associated facilities. Often the word stock refers to a population or part of the population of a single species but in the frequent case of multispecific fisheries it includes a group of at least two similar or diverse species.

Stock assessment is the part of fisheries science that studies the status of a fish stock as well as the possible outcomes of different management alternatives. It tells us if the abundance of a stock is below or above a given target point and by doing so lets us know whether the stock is overexploited or not; it also tells us if a catch level will maintain or change the abundance of the stock. But stock assessment is not the goal of fisheries science.

THE PURPOSE OF STOCK ASSESSMENT IN FISHERIES SCIENCE

Stock assessment makes use of diverse types of information to give managers advice about the status of fishery and the possible outcomes of management actions. This includes aspects not only related to the resource abundance such as whether the stock is depleted or close to its maximum biomass, but also in regards to other important aspects of fish population dynamics such as the current levels of mortality and expected levels of future recruitment, or even economically relevant features such as likely changes in catch per unit effort.

THE STOCK CONCEPT

When describing the dynamics of an exploited aquatic resource, a fundamental concept is that of the “stock”. A stock is a sub-set of a “species”, which is generally considered as the basic taxonomic unit. A prerequisite for the identification of stocks is the ability to distinguish
between different species. Because of the great number of different, but often similar, species observed in tropical fisheries their identification is problematic. The fishery scientist, however, must master the techniques of species identification if any meaningful fish stock assessment is to come out of the data collected.

**Fig – 18.2**

By a “stock” we mean a sub-set of one species having the same growth and mortality parameters, and inhabiting a particular geographical area. To this definition we can add that stocks are discrete groups of animals which show little mixing with the adjacent groups. One essential feature is that the growth and mortality parameters remain constant over the distribution area of a stock, so that we can use them for making assessments.

Stock assessment has been defined in many ways, often in terms of its objective. Sparre and Venema (1992) proposed that the basic purpose of stock assessment is “to provide advice on the optimum exploitation of aquatic living resources”. Probably the best modern definition comes from Hilborn and Walters (1992): “Stock assessment involves the use of various statistical and mathematical calculations to make quantitative predictions about the reactions of fish populations to alternative management choices”. The last definition is especially relevant because it explicitly says two important things, that *quantitative predictions* are needed in the process and that the objective is to provide advice to management about choices.

The most suitable definition in the context of fish stock assessment was given by Gulland (1983) who stated that for fisheries management purposes the definition of a “unit stock” is an operational matter, i.e., a sub-group of a species can be treated as a stock if possible differences within the group and interchanges with other groups can be ignored without making conclusions reached invalid.

This means that it is preferable to start by making stock assessments over the entire area of distribution of a species, as long as there are no indications that separate unit stocks exist in that area. If it becomes clear that the growth and mortality parameters differ significantly in various parts of the area of distribution of the species, then it will be necessary to assess the
species on a stock by stock basis. The identification of separate stocks is a complex matter, which usually requires many years of data collection and analysis. Fish stock assessment should be made for each stock separately. The results may (or may not) subsequently be pooled into an assessment of a multispecies fishery. Therefore, the input data must be available for each stock of each species considered. The stock concept is closely related to the concepts of growth and mortality parameters. The “growth parameters” are numerical values in an equation by which we can predict the body size of a fish when it reaches an age. The “mortality parameters” reflect the rate which the animals die, i.e., the number of deaths per time unit.

The essential characteristic of a stock is that its growth and mortality parameters remain constant throughout its area of distribution. Let us, as an example, partition that area into two parts, sub-areas A and B:

![Sub-area diagram](image)

The growth and mortality parameters must be the same in sub-areas A and B, or in other words:

1. The animals in sub-area A must have the same body growth rate as the animals in sub-area B.
2. The animals in sub-area A must have the same probability of death as the animals in sub-area B.

If fishing takes place only in sub-area A, it is assumed that each individual fish in the stock has the same probability of being encountered in the sub-area A and thereby also that it has the same probability of being caught. The individuals are supposed to move freely between the two sub-areas.

In order to determine whether a species from one or more distinct stocks, we should examine its spawning areas, growth and mortality parameters and morphological and genetic characteristics. We should also compare the fishing patterns in various areas and carry out tagging studies. The process is complicated, and often it is not possible with the knowledge in hand to determine whether there are several stocks of that species or not. There are two main reasons for failing to define a stock properly:

1. The full distribution area of the stock is not covered, so that only a part of the stock is considered, or the opposite.
2. Several independent stocks are lumped together, for example because their areas of distribution overlap.

Several countries may exploit the same stock. This is the case for many migratory stocks, e.g. tunas. It sometimes happens that a country assesses such a “shared stock” as if it were a national stock only exploited by that country. On the other hand, a fishery if a single country may exploit several independent stocks. Coral reef fish stocks may fall in this category.

**Quantitative predictions, dynamics, and uncertainty**

In order to be of practical use, modern fisheries stock assessment must be able to make quantitative predictions. To state that a fishery resource is “abundant” or “overfished” without
further detail is of limited use for shaping management decisions if the level of abundance or depletion is not expressed as a quantity such as “the fishable stock is at 30% of its original virgin biomass”. Equally important, stock assessment should be able to make quantitative predictions of the outcomes of different management regulations, such as how likely it is that an overexploited stock will recover to a target level in a specified time-frame under different catch or effort quotas. This is why modern stock assessment work is by necessity a quantitative discipline. While decades ago it was difficult to make these types of quantitative predictions, computers now allow us to do calculations we would hardly be capable of doing 20 years ago, and as time passes numerical methods are becoming more rigorous and powerful for stock assessment.

One of the most important roles of stock assessments is to understand the dynamics of fisheries. This follows because biological resources, fishermen and the environment are changing entities; they are dynamic not static. Furthermore, fisheries will necessarily respond dynamically over time to management actions as well as to external factors such as environmental forces. Understanding all of these dynamics in order to make good predictions is the ultimate role of stock assessment.

Uncertainty is an intrinsic characteristic of stock assessment. First, natural systems have a set of random variability that translates into uncertainty and which can be due to variations in fish growth (Fargo and Kronlund, 2000) and reproductive output, as well as to environmental effects (abiotic and biotic) on biological and ecological processes (Parsons et al., 1998). Other sources of uncertainty are the variations in the behaviour of fishing fleets and gear, the errors and biases in data collection, and the often incomplete or less than ideal quality of the data sets available for performing stock assessment. Uncertainty also arises from the choice of model used for stock assessment; some models are better suited to capture the underlying dynamics of a given resource than others but it is often impossible to determine which model is more correct for a particular stock. Considering all of the above, it is not surprising to find that the results of fisheries stock assessment are never precise estimates of biomass or...
mortality, but are in reality estimates that contain a certain degree of uncertainty and doubt. Dealing with uncertainty, acknowledging it and incorporating it into the decision-making process is something extremely important but that only recently has begun to be put into practice.

**The concept of MSY and its evolution from an objective to a reference point**

The traditional concept of the dynamics of the fishery resources is that there is an underlying model according to which as fishing effort increases, catch will increase up to a maximum, and if effort continues to grow then catches (also known as yield) will decrease. This leads directly to the concept of maximum sustainable yield (MSY) which has been the holy grail of fisheries (Larkin, 1997).

![Fig 18.4 - a graphical representation of the Maximum Sustainable Yield (MSY) concept.](image)

The specific shape of the yield curve shown in the Figure 1 does not matter. The important principle always holds: zero effort means zero catch; too much effort leads to small or almost zero catch. Also, in theory there should be a point at which catch has a maximum—at least on average—and supposedly once the curve reaches the top, the MSY level has been found. For decades, finding MSY and keeping fisheries at this prescribed level of catch and effort became the sole objective and obsession of fisheries science, as eloquently put by Larkin (1977).

There are several problems with this concept, the first practical problem being the natural systems have a lot of random variability. In practice, real data will always reflect this variability as “noise”. The great danger of focusing stock assessment work solely in finding MSY and its associated optimum effort ($f_{opt}$ defined as the effort level that produces MSY) is that we can seldom be totally sure that we have witnessed the MSY level. Even if managers try to be very careful and cautious by developing a fishery at a very slow pace it will never be guaranteed that the stock will not be overexploited or that opportunities will not be wasted. An excellent example of the difficulties in finding MSY comes from work on Atlantic yellowfin tuna (*Thunnus albacares*) published by FAO and cited by Hilborn and Walters (1992). When scientists performed the first assessment of this resource in the mid-1970s, they thought they had already arrived at the MSY level and calculated this about 50,000t. However, due to lack of effective management the fishery continued to grow and a second analysis 10 years later suggested a different MSY level of more than 100,000 t, clearly indicating that the first assessment lead to a “false” MSY. The question remaining was if the second assessment was also an underestimate.
The real problem in the above example and most real fisheries is that in all cases and especially in situations of noisy data we would have to go beyond MSY to make sure that we have actually found it. In other words until yield does not substantially decrease for a good period of time at increased effort levels we cannot be sure that MSY has been observed. This effectively means that we can never prevent overexploitation, at least not a small amount of it in the best case. This is an important principle identified by Hilborn and Walters (1992): “You cannot determine the potential yield from fish stocks without overexploiting them.” The secret is not to overexploit the stock beyond recovery in our effort to find MSY. An additional practical problem is that once fisheries have actually passed the MSY point and gone into the overexploitation phase, more problems arise. In such cases, the fishery is already in the overcapacity side of the curve. This leads to another sad but important principle stressed by Hilborn and Walters (1992): “The hardest thing to do in fisheries management is to reduce fishing pressure.”

In an ideal situation a new fishery should start with all the mechanisms in place to assure,

a) detection of MSY quickly after passing this point (i.e., a good monitoring and data acquisition system should be in place), and
b) There should be mechanisms in place from the onset of exploitation, to reduce effort effectively without detrimental effects (high taxes that can be later used to buy back boats or compensate for the lost catches and revenue of each boat).

Nowadays, MSY is a theoretical concept that should hold on average, but it is mostly useful as a general concept that helps us to guide our work; it is not the aim of fisheries assessment. In present times the MSY concept is used to derive management targets and limits or biological reference points (BRPs). Biological reference points are levels of total biomass, spawning stock biomass, fishing mortality rate or other measurable characteristics of a fish population and a fishery, which are either the target of management or a limit beyond which the fishery will not be permitted to go. Two common BRPs are the biomass at which the population can produce the maximum sustainable yield (B) MSY and the fishing mortality needed to achieve MSY (F). A further important consideration is that MSY and the reference points based on it assume that environmental conditions are constant. However, human-induced (habitat destruction, species depletion) and environmentally driven phenomena (climatic “regime shifts”), can all produce changes in MSY. This issue has commonly been either ignored or mishandled in fisheries science.

Model complexity and the importance of cross-comparison in stock assessment

Predictions are always based on the use of a model, whether the model is explicit or implicit. Even the simplest prediction about what will happen to a stock if effort is increased implies a set of assumptions or conceptual model. Formally, a model is just a representation or abstraction of a given system or process, which in the case of quantitative disciplines such as fisheries stock assessment takes the form of equations or sets of equations. The type and complexity of models depends on the field of research and the particular problem to be analyzed. In terms of Holling’s (1978) classification, problems in population modeling generally lie in the area of low quality/quantity of relevant data. However, it is important to emphasize that the complexity of a model (understood as the number of variables included) is not always directly related to its performance and usefulness. Models available for stock assessment range from the simple holistic models that intend to capture all biological processes in a simple equation such as surplus production models, to the detailed and elaborate age-
structured, spatially-structured, multi-stock or even multi-species models that include several sets of equations and which intend to give a more realistic representation of fish population dynamics. But while intuition tells us that complicated and detailed models should be better than simple ones because they more accurately represent “reality,” research has shown that simple models can often perform better because they require fewer parameters to be estimated, and very frequently the uncertainty surrounding the estimation of some of these parameters only reduces the ability of models to produce useful information (Ludwig and Walters, 1985; 1989; Ludwig et al., 1988). Readers are encouraged to investigate this topic in more detail by referring to chapter 3 of Hilborn and Walters (1992) for an excellent discussion and further references on this topic. Starfield and Bleloch (1986) give an excellent accessible introduction to model building.

MODELS:

A description of a fishery consists of three basic elements:

1. The input (the fishing effort, e.g. the number of fishing days)
2. The output (the fish landed) and
3. The processes which link input and output (the biological processes and the fishing operations)

Fish stock assessments aims at describing those processes, the link between input and output and the tools used for that are called “models”. A model is a simplified description of the links between input data and output data. It consists of a series of instructions on how to perform calculations and it is constructed on the basis of what we can observe or measure, such as for example fishing effort and landings.

The actual processes which go from a certain number of days fishing with a certain number of boats to a certain number of fish being landed are extremely complicated. However, the basic principles are usually well understood, so that by processing the input data by aid of models we can predict the output.

A model is a good one if it can predict the output with a reasonable precision. However, since it is a simplification of reality it will rarely (and only by chance) be exact.

The instructions for the calculations that make up the model are given in the form of mathematical equations. These are composed of three elements: “variables”, “parameters” and “operators”. For example, the mathematical equation:

\[ y = 2.5 + 3x \]

has the variables y and x, the parameters 2.5 and 3 and the operators “+” and “*”. The equation is used to predict the value of y for some value of x.

GENERAL PROCEDURE OF FISH STOCK ASSESSMENT
Fish stock assessment involves five basic steps as illustrated in Fig. 2. The first step is to collect data on the fishery, the INPUT to the assessment, which often have to be supplemented by assumptions or qualified guesses. Then we process the data by applying a model to estimate the growth and mortality parameters, the OUTPUT from the processing of “the historical data”. (The term “historical” is used to distinguish it from the subsequent process, the prediction of future yield.) This prediction is based on the previous OUTPUT (= INPUT) and on a model, and the prediction is repeated for a series of alternative options. (Such options could be, for example, a fishing effort reduction of 10%, 20% and 30%, no change in fishing effort or a fishing effort increase of 10%, 20% and 30 %.) Among the alternative assumptions the best one is eventually selected as the final OUTPUT. The original INPUT data may be research survey data, data from samples drawn from the commercial fisheries or a combination of both.

![General flow-chart for fish stock assessment](image)

**Fig – 18.5-** General flow-chart for fish stock assessment

Two main groups of fish stock assessment models are described here: “holistic models” and “analytical models”. The simple holistic models use fewer population parameters than the analytical models. They consider a fish stock as a homogenous biomass and do not take into account, for example, the length or age-structure of the stock. The analytical models are based on a more detailed description of the stock and they are more demanding in terms of quality and quantity of the input data. On the other hand, as compensation, they are also believed to give more reliable predictions.

The type of model to be used depends on the quality and quantity of input data. If data are available for an advanced analytical model then such a model should be used, while the simple models should be reserved for situations when data are limited. We are often in the situation where a complete set of input data for an analytical approach is not available, but where the available data exceed the demand for the simple models. As an alternative to using simple models in this case, the lacking input data can be replaced by assumptions or qualified guesswork. Often, the lacking parameter for a particular stock can be replaced by known parameters from another, similar stock.

**Analytical models**

A basic feature of analytical models as developed by, among others, Barnov (1914), Thompson and Bell (1934) and Beverton and Holt (1956), is that they require the age
composition of catches to be known. For example, the number of one year old fish caught, the number of two year old fish caught, etc. may form the input data.

The basic ideas behind the analytical models may be expressed as follows:

1. If there are “too few old fish” the stock is **overfished** and the fishing pressure on the stock should be reduced.
2. If there are “very many old fish” the stock is **underfished** and more fish should be caught in order to maximize the yield.

The analytical models are “age-structured models” working with concepts such as mortality rates and individual body growth rates.

The basic concept in age-structured models is that of a “cohort”. To put it simply, a “cohort” of fish is a group of fish **all of the same age belonging to the same stock**. For example, a cohort of the threadfin bream, (*Nemipterus marginatus*) could be all the fish of that species that hatched from June to August in 1976 near Tanjung Pinang in the South China Sea. Suppose there were one million specimens in that cohort, after August 1976 the original one million fish would gradually decrease in number because of deaths due to natural caused (predation, diseases, etc.) or fishing. However, while the number of survivors of the cohort decreases with time the average individual body length and body weight increases.

Fig. 3 shows an (hypothetical) example of the dynamics of a cohort, in the form of plots against age of the number of survivors (A), body length (B), body weight (C) and total biomass (D). curve A shows the decay in the number of survivors as a function of the age of the cohort. Curve B shows how the average body length increases as the cohort grows older. Curve C shows the corresponding body weight, while curve D is a plot of the total biomass of the cohort, i.e. the number of survivors times the average body weight against the age of the cohort.

It should be noted that curve D has a maximum (at age A1). Thus, to get the (hypothetical) maximum yield in weight from that cohort all fish should be caught exactly when the cohort has reached age A1. This, of course, is not possible in practice. However, we may say that the goal of fish stock assessment is to manage fisheries in such a way that catches come as close as possible to this theoretical maximum.
The implication is that the fish should neither be caught too young nor too old. If the fish are caught too young there is “growth overfishing” of the stock.

There are thus two major elements in describing the dynamic of the cohort:

1. The average body growth in length and weight.
2. The death process.

**Holistic models**

In situations where data are limited, for example, when starting up the exploitation of an hitherto unexploited resource, or in cases of limited capability of sampling, one may not have input data of the quality and in the quantity required for an analytical model. One solution would be to start up the collection of the data types required for the analytical approach and then wait until a sufficient amount is available. This approach is, of course, recommendable, because it solves the problem in the long run, but that may take years, while often advice on an exploitation or development strategy may be needed now. No matter which type of data we have, there is always some information to be extracted from it, and that advice based on an analysis of a limited data set is usually better than complete guesswork.

In order to cover such data-limited situations, some simple holistic, less data demanding methods have been included in the manual. These methods disregard many of the details of the analytical models. They do not use age or length structures in the description of the stocks, but consider a stock as a homogenous biomass.

Two types of simple methods are presented, namely the “swept area method” and the “surplus production model”.

The swept area method is based on research trawl survey catches per unit of area. From the densities of fish observed (the weight of the fish caught in the area swept by the trawl) we obtain an estimate of the biomass in the sea from which an estimate of the MSY is obtained. This method is rather imprecise and it predicts only the order of magnitude of MSY.
The surplus production methods use catch per unit effort (for example kg of fish caught per hour trawling) as input. The data usually represent a time series of years and usually stem from sampling the commercial fishery. The models are based on the assumption that the biomass of fish in the sea is proportional to the catch per unit of effort as shown in the Fig 5. An estimate of the yield is obtained by multiplying effort by catch per unit of effort.

**ESTIMATION OF GROWTH PARAMETERS**

The study of growth means basically the determination of the body size as a function of age. Therefore all stock assessment methods word essentially with age composition data. In temperate waters such data can usually be obtained through the counting of year rings on hard parts such as scales and otoliths. These rings are formed due to strong fluctuations in environmental conditions from summer to winter and vice versa.

Only recent methods have been developed to use much finer structures, so-called daily rings, to count the age of the fish in number of days. These methods, however, require special expensive equipment and a lot of manpower, and it is therefore not likely that they will be applied on a routine basis in many places.

Fortunately several numerical methods have been developed which allow the conversion of length-frequency data into age composition. Although these methods do not require the reading of rings on hard parts, the final interpretation of the results become much more reliable if atleast some direct age readings are available.

**THE VON BERTALANFFY GROWTH EQUATION:**

Putter (1920) developed a growth model which can be considered the base of most other models on growth including the one developed as a mathematical model for individual growth by von Bertalanffy (1934), and which has been shown to conform to the observed growth of most fish species. The von Bertalanffy growth model of body length as a function of age is explained here. It has become one of the cornerstones in fishery biology because it is used as a sub-model in more complex models describing the dynamics of fish populations. Fig. 6 illustrates the model in graphical as well as in mathematical form.

The mathematical model, B, expresses the length, L, as a function of the age of the fish, t:

\[ L(t) = L_\infty \times (1 - \exp(-K(t-t_0))) \]

The right hand side of the equation contains the age, t, and some parameters. They are: “\(L_\infty\)” (read “L-infinity”), “K” and “\(t_0\)” (read “t-zero”). Different growth curves will be created for each different set of parameters, therefore it is possible to use the same basic model to describe the growth of different species simply by using a special set of parameters for each species.

The most important message that readers should take home is that while analyzing a fishery, it is imperative to avoid using a single “best” method; the idea that any given model is the best and only model to be used for fisheries stock assessment is dangerously wrong. Instead, it is best to employ a carefully chosen suite of methods—considering the available data—and if possible including both simple and complex models. This will allow the cross-comparison of alternative results that helps detect coincidences and patterns as well as inconsistencies, often highlighting errors in data or guiding the acquisition of additional key information through additional research. In a similar fashion, conflicting results using the same model with different
data sets should be carefully analyzed for possible biases in the data. Stock-assessment scientists should ask themselves why there might be differences in predictions about the status of the stock or about the outcomes of different management alternatives across models. An objective picture of the situation can only be obtained when we question the conclusions from one analysis with those of a different one and critically use the different results to gauge our conclusions and to identify which pieces of the puzzle are missing. Only this complete process will allow us to improve the data and methods, and therefore increase the capacity to perform better assessments in the future. The same principle applies also to different data sets that could be available to perform a particular stock assessment. Sound stock assessment is achieved only through healthy cross-comparison and exhaustive questioning of the results of alternative models and data sets.

Finally, it should be mentioned that the complex and often politically charged topic of model choice in stock assessment can nowadays be dealt with through the use of Bayesian approaches (Hammond and O’Brien, 2001) and decision analysis techniques (Punt and Hilborn, 1997; McAllister and Kirkwood, 1998). These methods offer quantitative ways to choose between different models and management options taking into account the uncertainty involved, and are the best way to make management decisions based both on the outcomes of the stock assessment and the probabilities of success of the proposed management options.