A Guide to Fisheries Stock Assessment

From Data to Recommendations

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Fish are born, they grow, they reproduce and they die – whether from natural causes or from fishing. That's it. Modelers just use complicated (or not so complicated) math to iron out the details.

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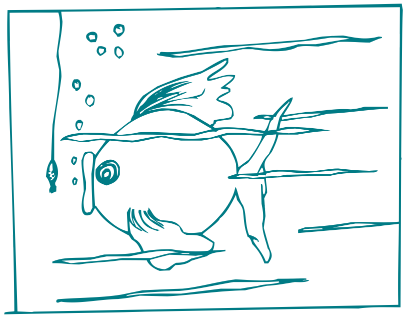
Contents



Stock Assessments: An Introduction

1

Fishery managers have a range of goals. They strive to maintain healthy fish populations and a healthy fishing industry while still preserving vital recreational communities. To achieve their goals, managers rely on a collection of tools, including quotas, size limits, gear restrictions, season timing and area closures. But how do decision makers determine which combinations of tools will best accomplish their objectives? To choose the best approach to managing a fish stock, managers must equip themselves with as much information as possible.

A stock assessment provides decision makers with much of the information necessary to make reasoned choices. A fishery stock assessment describes the past and current status of a fish stock. How big is the stock? Is it growing in size or shrinking? A stock assessment also attempts to make predictions about how the stock will respond to current and future management options. Will a slight increase in fishing pressure have a negative effect on the stock next year? Ten years from now? In the end, the manager must decide how to interpret the information from the stock assessment and determine which options are best overall.

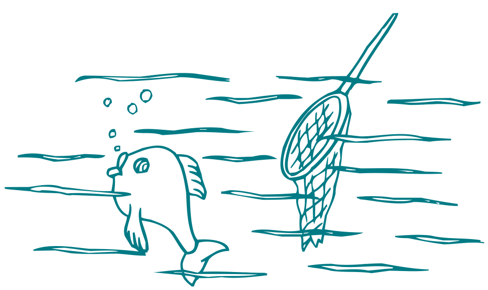
A complete stock assessment contains a vast array of information on both the fish population and the fishery itself. A fish **population** is a group of individual fish of a single interbreeding species located in a given area, which could be as large as the Atlantic Ocean or as small as a single river. A fish **stock**, on the other hand, is defined as much by management concerns – such as jurisdictional boundaries or harvesting location – as by biology. For example, alewives from the Taylor River are considered a separate population from those in the Lamprey River, but both are part of the Gulf of Maine alewife stock.

A stock assessment provides decision makers with the information necessary to make reasoned choices.

Within a fish stock or population, a **cohort** is a group of fish all born in the same year. Within the Gulf of Maine cod stock, all of the cod born in 2004 belong to one cohort and those born in 2005 comprise a second cohort. Stock assessments often track a cohort over time. Short-term increases or decreases in the size of a particular stock can sometimes be explained by the existence of an exceptionally large or small cohort.

A stock assessment describes a range of life history characteristics for a species, such as information (derived from other studies) about age, growth, natural mortality, sexual maturity and reproduction; the geographical boundaries of the population and the stock; critical environmental factors affecting the stock; feeding habits; and habitat preferences. Drawing on the knowledge of both fishermen and scientists, stock assessments give qualitative and quantitative descriptions of the fishery for a species, past and present. Final stock assessment reports also contain all of the raw data used in the assessment and a description of the methods used to collect that data.

The mathematical and statistical techniques used to perform a stock assessment are referred to as the **assessment model**. Scientists compare different assumptions within a given assessment model and may also examine a variety of different assessment models. Ultimately, stock assessment scientists will estimate the current status of the stock relative to management targets and predict the future status of the stock given a range of management options. They will also describe the most likely outcomes of those options and the uncertainty around those outcomes.



This publication is not designed to be an all-inclusive description of data and methods used for stock assessments. Rather, the goal of this document is to provide an overview of how stock assessment scientists and managers turn data into recommendations. We assume readers have some working knowledge of the fisheries management process, but no modeling or statistics background is necessary.

We'll discuss the range of data that might be available to scientists and the types of information a stock assessment provides. We'll then describe the range of population dynamics models (from the simple to the complex) that can underlie the assessment model. Finally, we will discuss how stock assessment scientists merge data and models to determine the status of the stock and generate recommendations. A glossary in the back of this publication defines the technical terms associated with stock assessment science.

Recommended Reading

Our goal is to provide readers with a basic understanding of the stock assessment process. For readers

What Types of Data are Available?

2

Data used in stock assessments can be categorized as either fishery-dependent or fishery-independent. **Fishery-dependent data** are derived from the fishing process itself and are collected through such avenues as self-reporting, onboard observers, portside surveys, telephone surveys or vessel-monitoring systems.

Fishery-independent data are derived from activities that do not involve the commercial or recreational harvest of fish, such as trawl, acoustic, video and side-scan sonar research surveys and some tagging experiments. Stock assessments generally require data on catch, relative abundance and the life history of the species in question. Both fishery-dependent and fishery-independent data can help fulfill these needs.

Fishery-Dependent Data

Landing Records

The most common sources of fishery-dependent data are landings records and port samples. Landing records, which result directly from the sale of caught fish, provide information only on landed catch. The data is often in the form of total weight and rarely in total numbers of fish.

When the market for a given species has multiple size categories, the landing records can give some coarse information on the size distribution of the catch, but such information is rarely precise enough to be used directly in a stock assessment. Other forms of data are required to sort out these landing records into specific size or age distributions.

Portside Sampling

Some portion of both recreational and commercial catch is sampled on the docks for size and age by government scientists known as portside observers or port agents. When the observers are sampling from recreational fishermen, the survey is called a **creel survey.** In sampling both recreational and commercial catch, the size of a fish is measured on site. Determining a fish's age, however, requires taking biological samples to be evaluated in a lab. Scientists can determine a fish's age by counting the growth rings in a scale or an **otolith** (ear bone), much like counting the rings of a tree.

Because a fish's age must be determined in a lab, many more length samples are taken than age samples. Scientists then estimate the length frequency, or the total number of landed fish in each length class. These estimates are calculated for each type of fishing gear separately, as each gear may have its own length-frequency distribution.

For example, if 80 percent of the fish sampled from a gill net fall within a given size range, it is assumed that 80 percent of the total number of fish landed by that gill net fall within this size range. But gill nets with larger or smaller mesh sizes would have their own length-frequency distributions. If length-sampling data is sparse, though, scientists may not have enough information to reliably estimate the length distribution.

By taking both size and age samples from a number of individual fish, scientists can determine how to estimate the age of a fish based on its length. Fisheries scientists use these estimates to develop a **length-age table,** or length-age key. This table allows a stock assessment scientist to convert the length distribution of the landed catch (which is based on many, many samples) into an age distribution of the landed catch.

Onboard Observers

To gain a broader understanding of the ways in which commercial fishermen interact with a range of species, government personnel known as **onboard observers** sometimes accompany fishing vessels. Observers are trained to sample catch for size, and sometimes age, and to estimate bycatch and discards.

Bycatch are the fish caught during the fishing process that were not specifically targeted for harvest. Not all bycatch is discarded. Some bycatch is landed and recorded by landing records or portside observers. Bycatch that are thrown back (because they were the wrong size, sex or species, or because trip limits or quotas were met) are called **discards**. All discards are a form of bycatch. Only a portion of the discarded bycatch will survive the catch and discarding process, which means that the estimate of landed catch will underestimate, sometimes quite severely, the total amount of fishing-related mortality.

Usually only a portion of the vessels in a fishery carry onboard observers. To generate a fleet-wide estimate of discards, scientists assume that the unobserved vessels behave in the same fashion as the observed vessels. Scientists often calculate the length-frequency distribution of the discards, which allows them to estimate the number of fish discarded for each length class for the entire fleet. Drawing on length-age tables, scientists can then estimate the number of discards in each age class.

Any fish caught that were not specifically targeted for harvest are called bycatch. Bycatch that are thrown back are known as discards.

In the absence of onboard observers, scientists are forced to make assumptions about how many fish are discarded. They often set the amount of discards equal to some proportion of the landed catch, based on previous research. Scientists also refer to previous research to estimate the discard mortality (the rate at which the discarded fish die.)

Log Books and Vessel Trip Reports

In some commercial fisheries, either as a requirement or as an organized voluntary effort, fishermen keep their own records, called **log books** or vessel trip reports, which they pass on to government officials. Data from landing records and onboard observers are generally considered more reliable than log books in terms of estimating landed total weight and numbers. Nevertheless, the log books can be incredibly valuable for determining the spatial distribution and amount of effort in the fishery. In some fisheries, boats also use electronic devices that automatically record the location of a vessel, called **vessel monitoring systems.**

Telephone Surveys

The primary method for collecting data on recreational fisheries is through a telephone survey conducted as part of the National Marine Fisheries Service's Marine Recreational Fishery Statistics Survey (MRFSS). Scientists use this survey to estimate the number of recreational fishing trips that target a specific species and those that merely encounter a specific species, even if that species isn't targeted.

Each fish encountered during a trip falls into one of three categories: caught and sampled by portside observers (labeled type A fish), caught but not sampled by portside observers (type B1 fish), or caught but thrown back (type B2 fish). An estimated percentage of type B2 fish is assumed to die as a result of the catch-and-release process, based on information from other studies.

For the purposes of stock assessment, the total mortality associated with the recreational fishery equals all the fish caught and sampled by portside observers, all the fish caught and not sampled, and an estimated portion of the fish that were thrown back. Scientists take the survey data and estimate the number of fish caught in each length class by applying the length-frequency data from portside sampling to the estimated total number of fish caught.

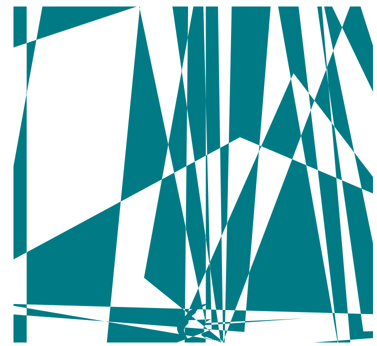
Fishery-Independent Data

The vast majority of fishery-independent data comes from research surveys conducted by the federal or state governments. Scientists take samples throughout the potential range of the target fish using standardized sampling gear including trawls, seines, hydroacoustics and video. These surveys can target a group of several species (such as the Northeast Fisheries Science Center bottom trawl survey), a single species (such as the Northeast Fisheries Science Center herring survey), or even a specific age-class of a specific species (such as beach seine surveys for young-of-the-year bluefish).

Regardless of the target or the gear, maintaining standard survey practices over time is crucial. Changes in mesh size, soak times and tow length or speed can all impact the comparability of a survey over time. Whenever new gear or sampling methods are adopted, they should be calibrated so that results can be directly compared to results from the old gear or method. By sampling across the potential range of the fish, rather than just its current range, the survey can detect shifts in distribution, including range contraction or expansion.

The survey data provide an index of fish abundance, typically the number of fish caught per unit of effort (such as the number of fish per tow). Surveys can also provide information on the size and age distributions of the stock, estimates of the percentage of fish mature at each age, and size-age relationships (similar to those derived from portside or onboard observation of the catch). By sampling stomach contents, survey scientists can even determine a species' diet.

Results from tagging, mark-and-recapture and other studies typically fall under the category of fishery-independent data. Such studies may estimate the movement or migration rates between stocks, the natural mortality rate of the fish, the reproductive output of the fish, growth rates, maturity schedules (the percent of individuals mature at each age), and hooking or discard mortality rates. All of this information enhances stock assessment models.



Biological Reference Points

3

Through stock assessments, scientists attempt to estimate the amount of fish in a stock and the rate of fishing mortality. They do so with regard to a stock's **biological reference points.** A biological reference point is a concrete number, a value for, say, stock size or fishing mortality. A stock assessment produces a series of estimates for stock size and fishing mortality over time. Biological reference points serve as a way to judge those estimates based on knowledge and assumptions about the species' growth, reproduction and mortality.

Biological reference points give decision makers guidance in determining whether populations are too small or fishing pressure is too great. They help provide targets for how large the population or how intense the fishing pressure should be.

Why do we care about the **fishing mortality rate**? In its simplest form, the fishing mortality rate is the rate at which fish are removed from the stock by harvesting. Think of a fish stock as money in an interest-bearing bank account. If the interest is five percent per year, the bank account balance will grow as long as you withdraw less than five percent per year. If you withdraw more than five percent per year, the bank principal will decrease. If you do that consistently, you'll eventually empty the account.

The interest rate in this example is equivalent to the stock's growth rate. The withdrawal rate is equivalent to the fishing mortality rate. Biological reference points based on fishing mortality help managers keep the withdrawal rate at a level that will ensure the long-term production or stability of the stock.

The concept of **maximum sustainable yield** (MSY) serves as the foundation for most biological reference points. The maximum sustainable yield is typically thought of as the largest average catch that can be continuously taken from a stock under existing environmental conditions. That is, maximum sustainable yield is the greatest number of fish that can be caught each year without impacting the long-term productivity of the stock.

Stock assessment scientists and decision makers use the letter *B* to denote **biomass,** the total weight of the fish in a given stock. Occasionally, rather than total biomass, scientists will refer to the **spawning stock biomass** (SSB), the total weight of the reproductively mature individuals in the stock. The term B_{MSY} is used to indicate the stock size that can produce the maximum sustainable yield. The term SSB_{MSY} indicates the size of the reproductive mature portion of the stock that will produce the maximum sustainable yield. Similarly, the letter *F* denotes the fishing mortality rate, while F_{MSY} indicates the fishing mortality rate at the level that would maintain the maximum sustainable yield for a stock at B_{MSY}.

Fisheries scientists aim to determine a stock's **optimum yield,** the amount of catch that will provide the greatest overall long-term benefit to society. The optimum yield must take into account the biology inherent in maximum sustainable yield, as well as economics and the attitudes of the public towards risk and environmental protection. The optimum yield can never be greater than maximum sustainable yield. In some cases scientists may set optimum yield equal to maximum sustainable yield, but they often set it at a value less than maximum sustainable yield.

In theory, if the environment is constant a fishery should be able to produce an average catch equal to maximum sustainable yield for eternity. By environment we mean everything from water temperature and habitat composition to predator and prey abundance – anything that affects the birth, growth or death rates of a fish. That's a pretty tall order.

The environment is anything but constant and the ability of fisheries managers to control harvest from year to year can, in some situations, be quite shaky. Despite this, the concept of maximum sustainable yield serves as the underpinning for many of the biological reference points that are evaluated in a stock assessment.

Targets versus Thresholds

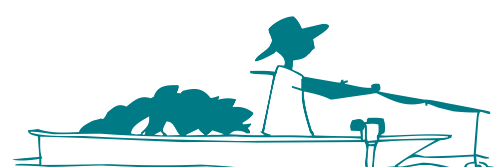
Biological reference points provide quantitative values for targets and thresholds. **Targets** are values for stock size and fishing mortality rate that a manager aims to achieve and maintain. Targets are determined by a combination of biological and socioeconomic factors. This is where optimum yield comes into play. Should the population target be B_{MSY} or something larger than B_{MSY}? Should the target fishing mortality rate be F_{MSY} or something lower? Should the target fishing mortality rate be managed to provide for a relatively constant catch? Or should it allow for a relatively constant effort, within an acceptable range of fishing mortality rates?

Deviations from the targets may or may not result in changes in policy. **Control rules**, designed by scientists but chosen by managers, guide the ways in which the fishing mortality rates are adjusted over time based on the status of the stock.

While targets are levels that managers aim for, **thresholds** are levels they aim to avoid. Thresholds are also referred to as **limits**, especially in the realm of international fisheries policy. A threshold is often defined as a specific fishing mortality rate or stock size that is some fraction of B_{MSY}. Consider again the bank account example described earlier. If you begin to withdraw more money than your account is earning through interest, you've crossed a threshold. When a fishery crosses a threshold, the stock is being depleted too quickly and actions must be taken to correct the situation.

Two of the key questions that a stock assessment aims to address are whether **overfishing** is occurring and whether the stock is in an **overfished** state. Although they sound similar, they are actually two distinct concepts. Overfishing occurs when the fishing mortality rate exceeds a specific threshold. The stock is being depleted too quickly, but the stock size may still be fairly large. Conversely, a stock is determined to be overfished when stock size falls below a specific threshold, either in terms of numbers or biomass of fish.

A stock may fall into any of four categories with regard to overfishing and being in an overfished state. (See ***Overfished or Overfishing?*** page 13.) In 2004, for example, the fishing mortality rate for Georges Bank Atlantic cod was determined to be greater than the fishing mortality threshold. The same year, the spawning stock biomass for Georges Bank Atlantic cod fell well below the spawning stock biomass threshold. In other words, overfishing was occurring *and* the stock was overfished.



Overfished or Overfishing?

Stock assessments attempt, in part, to determine whether overfishing is occurring and whether a stock is in an overfished state. While the two concepts are obviously related, they are not identical. Overfishing occurs when the fishing mortality rate (F) is greater than the fishing mortality threshold ($F_{threshold}$). A stock is overfished when the stock size (B) falls below the stock size threshold ($B_{threshold}$). Fish stocks fall into one of four categories based on these principles.

	$B < B_{threshold}$	$B \geq B_{threshold}$
$F \geq F_{threshold}$	Stock is overfished & Overfishing is occuring	Stock is not overfished but Overfishing is occuring
$F < F_{threshold}$	Stock is overfished but Overfishing is not occuring	Stock is not overfished & Overfishing is not occuring

If a stock is overfished, or if overfishing is occurring, managers are required by law to put measures in place to correct the situation. While the stock assessment produces estimates of the fishing mortality rate and stock size, the choice of thresholds is dictated by government policy. In the case of federally managed species, the policies are known as the National Standard Guidelines. These policies have evolved over time and have involved a fair bit of debate between scientists.

Determining Thresholds

In order to manage a stock, decision makers must define a **stock size threshold** ($B_{threshold}$), also called a **minimum stock size threshold.**

As discussed previously, the stock size that can produce the maximum sustainable yield is known as B_{MSY}. The stock size threshold can be defined in one of two ways, both of which are relative to B_{MSY}. The stock size threshold may be defined simply as a percentage of B_{MSY} – typically half (but never less than half) of B_{MSY}. Alternatively, the stock size threshold can be defined as the smallest stock size that could grow to B_{MSY} in 10 years if the fishing mortality rate was as low as possible (which might not be zero, depending on fishermen's ability to avoid bycatch). Current law requires the stock size threshold to be set equal to the larger of these estimates.

Determining the **fishing mortality threshold** ($F_{threshold}$), or **maximum fishing mortality threshold,** is a much more complicated matter than determining the stock size threshold. Because managers attempt to keep the stock at or above B_{MSY}, the fishing mortality threshold should be less than the fishing mortality that would produce B_{MSY} – that is, less than F_{MSY}. Given that the estimate for natural mortality (M) is an upper limit for F_{MSY}, the fishing mortality threshold for many fish stocks should also be less than the natural mortality rate. How much less is a function of the reproductive capacity of the stock.

A variety of methods exist to estimate fishing mortality thresholds. Some fishing mortality thresholds are based on "yield-per-recruit" analyses, where yield is the expected weight of fish caught by the fishery and **recruits** are fish at the youngest age entering the fishery. Yield-per-recruit analyses are performed in the last stages of the stock assessment and will be discussed in greater detail later.

Yield per recruit depends on the growth rates of individual fish, natural mortality and fishing mortality. In the simplest sense, if it was possible to catch fish of just one optimal age, one would maximize the yield per recruit

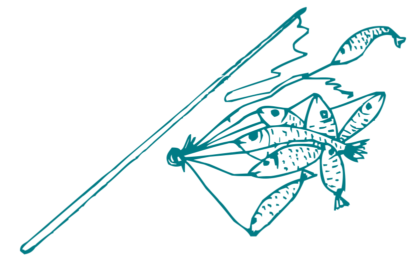
by catching all fish at exactly that age, when the percentage of fish dying of natural causes equaled the percent weight gained by the fish.

For example, if 10 percent of a cohort of equally sized fish will die due to natural causes between now and next fishing season, but the cohort will increase in weight by 15 percent during that same time period, then this cohort will still be five percent larger, in terms of weight, next year. Ignoring changes in price and the value of a dollar today versus a dollar tomorrow, one would be better off waiting to fish the cohort next year.

The yield per recruit (the total weight of fish caught divided by the number of fish from that cohort that originally entered the stock) would increase over the year, and fishermen would get a higher yield by waiting. But if the cohort would only increase in weight by 10 percent, a fisherman would get the same yield this year, in terms of weight, as he or she would the next year. If the cohort only increased in weight by eight percent, it would have a smaller total weight next year and one would be better off harvesting the fish this year.

The fishing mortality rate that achieves a maximum yield per recruit is called F_{max}. However, F_{max} is often greater than F_{MSY} and can lead to unsustainable harvest levels and an anti-conservative fishing mortality threshold. Much of this is due to the fact that F_{max} does not take the reproductive viability of the remaining stock into account. When the fishing mortality rate does exceed F_{max}, it's called **growth overfishing**.

When growth overfishing occurs, the stock is being harvested at a rate that does not allow it to maximize its potential yield per recruit. In other words, mortality rates are outpacing growth rates in terms of the overall weight or biomass of the stock.



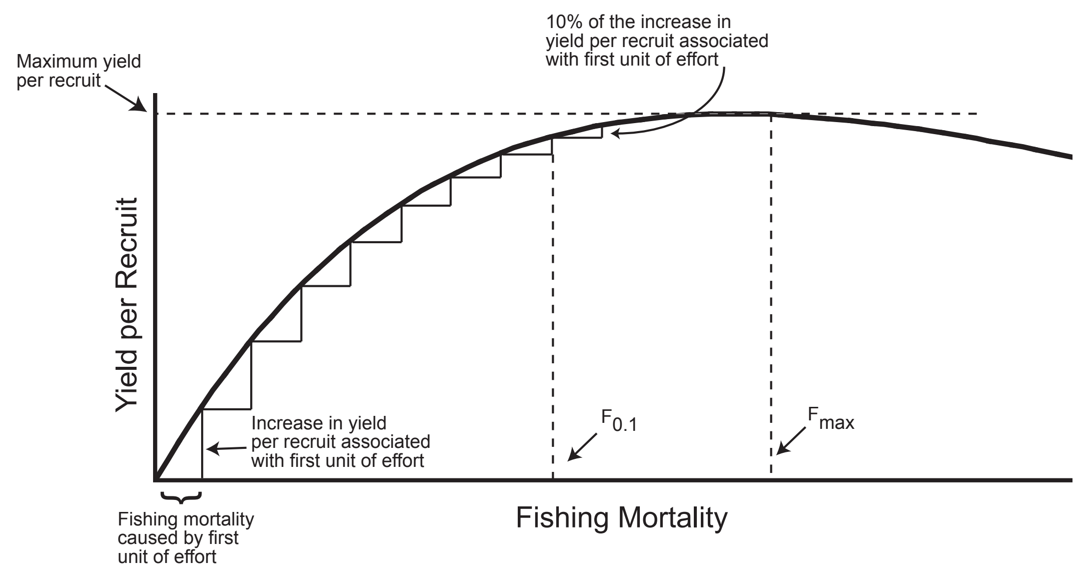
To combat the anti-conservative nature of F_{max}, researchers developed an alternative measure based on yield-per-recruit analyses called $F_{0.1}$. (See ***Calculating Fishing Mortality Thresholds***, page 15.) This analysis is based on the amount of fishing effort, described in terms of "units of fishing effort." In a recreational fishery, a single "unit of fishing effort" could be defined as one fisherman fishing for one day. In a trap fishery, it might be defined based on a trap of standard size soaking for one day. For trawl fisheries, defining one "unit of fishing effort" would involve factors such as vessel size, net size and the like.

Imagine that we add one standardized "unit of fishing effort" to a stock that has been in an unfished state and maintain that effort over time. The outcome of this increase in one unit of fishing effort is a specific fishing mortality rate and a specific yield per recruit. Adding a second unit of effort (a second fisherman fishing for one day, for example) will increase the fishing mortality and the fishery's yield per recruit,

Calculating Fishing Mortality Thresholds

Some fishing mortality thresholds are based on "yield-per-recruit" analyses, where yield is the weight of fish caught by the fishery and recruits are fish at the youngest age entering the fishery. In the real world, fishing at a level equal to F_{max} (the maximum yield per recruit) can lead to unsustainable harvest levels. Instead, researchers developed $F_{0.1}$, a more conservative measure based on yield-per-recruit analyses. This analysis is based on "units of fishing effort."

If fishermen apply a single "unit of fishing effort" to a previously unfished stock, the outcome will be a specific yield per recruit. With each additional increase in units of fishing effort, yield per recruit will increase – but it will do so by a smaller and smaller margin. Eventually, increasing fishing effort will actually lead to *decreasing* the yield per recruit, when fishing mortality is greater than F_{max}. In other words, increasing fishing pressure will increase yield, up to a point. Beyond that point, though, increasing fishing pressure will result in harvesting more fish than the number of young fish entering the fishery. Past this point (F_{max}), yield per recruit will decrease. Using $F_{0.1}$ as a threshold results in a fishing mortality rate that is lower than F_{max}, and it has proven to be relatively conservative.



but the amount of that increase will be less than the increase from zero effort to one unit of effort.

With each additional increase in fishing effort, the yield per recruit will increase by a smaller and smaller margin. Eventually, increasing effort, and therefore fishing mortality, will not increase the overall yield per recruit and will even lead to *decreasing* the yield per recruit, when fishing mortality is greater than F_{max}. This is called **decreasing marginal rates of return**, as each additional unit of effort produces smaller and smaller increases in yield per recruit.

The value of $F_{0.1}$ equals the fishing mortality rate when the increase in yield per recruit from adding a single unit of effort is only 10 percent of the increase achieved by going from zero to one unit of effort. The value of 10 percent was chosen somewhat arbitrarily based on simulation models developed by scientists. But using $F_{0.1}$ as a threshold results in a fishing mortality rate that is lower than F_{max}, and it has proven to be relatively conservative.

Another set of potential fishing mortality thresholds is based on spawning-stock-per-recruit analyses, where spawning stock is the amount, in numbers or in weight, of reproductively mature individuals in the stock. As with yield-per-recruit analyses, these analyses are performed in the last stages of a stock assessment.

As fishing pressure increases, the biomass of reproductively mature fish created by recruits entering the stock decreases. Essentially, the more you catch the fewer survive. The **maximum spawning potential** (MSP) is the biomass of reproductively mature fish per recruit *in the absence of fishing*. Fishing mortality thresholds (in the form of $F_{\%}$) equal the fishing mortality rate that reduces the spawning stock per recruit to a given percentage in the absence of fishing.

Spawning stock is the amount, in numbers or in weight, of the reproductively mature individuals in a stock.

For example, $F_{40\%}$ is the fishing mortality rate that reduces the spawning stock per recruit to 40 percent of that which would exist in the absence of fishing. A fishing mortality threshold set to $F_{40\%}$ is relatively common.

On rare occasions, the stock size threshold itself, rather than the fishing mortality threshold, is based on a percentage of the maximum spawning potential. For example, the stock would be considered overfished if the spawning-stock-per-recruit value was below some threshold percentage of maximum spawning potential.

A final set of potential fishing mortality thresholds combines the spawning stock per recruit and the assumed relationship between this year's spawning stock biomass and the number of recruits expected for next year.

Without going into the mathematical details of how these are created, F_{med} (sometimes called F_{rep}) is the fishing mortality rate that will allow the spawning stock biomass to replace itself with new recruits 50 percent of the time, given the observed recruitment history. In other words, if future recruitment is similar to past recruitment, fishing at a rate equal to F_{med} will remove less spawning stock biomass than the new recruits will contribute 50 percent of the time, but will remove more biomass than the new recruits will contribute 50 percent of the time.

The value F_{low} is the fishing mortality rate that will result in the spawning stock replacing itself, given historical levels of recruitment, 90 percent of the time. (That is, fishing will remove less biomass than new recruits will contribute 90 percent of the time.) The value F_{high} lies on the opposite end of the spectrum. F_{high} is the fishing mortality rate that will result in the spawning stock biomass replacing itself only 10 percent of the time. One way to remember these is that F_{low} has a low probability of stock decline whereas F_{high} has a high probability of stock decline.

Again, a stock assessment will produce estimates for these threshold values, but the choice of which threshold is appropriate is often based on predetermined policies. The risk of stock collapse is one of the aspects incorporated into

Terms at a Glance

F .... fishing mortality rate

B .... stock size, in terms of biomass

F_{MSY} .... fishing mortality rate at the level that would produce maximum sustainable yield from a stock that has a size of B_{MSY}

B_{MSY} .... stock size that can produce maximum sustainable yield when it is fished at a level equal to F_{MSY}

$B_{threshold}$ .... stock size threshold, the threshold below which a stock is overfished

$F_{threshold}$ .... fishing mortality threshold, the fishing mortality rate that causes a stock to fall below its stock size threshold

F_{max} .... fishing mortality rate that achieves maximum yield per recruit

$F_{0.1}$ .... the fishing mortality rate when the increase in yield per recruit from adding a single unit of effort is only 10 percent of the increase achieved by going from zero to one units of effort

$F_{\%}$ .... fishing mortality rate that reduces the spawning stock per recruit to a given percentage of the maximum spawning potential, in the absence of fishing

these policies. Short-lived, highly reproductive species may be able to sustain a higher fishing mortality threshold and lower stock size threshold than a long-lived species with a low reproductive rate.

More uncertainty will exist in estimates for fishing mortality threshold and stock size threshold for species with poor data. This greater uncertainty will increase the chance that the estimates are too high or low, thus increasing the chances of setting policies that may actually lead to a stock collapse. In such data-poor situations, scientists may choose a more conservative measure of fishing mortality threshold or stock size threshold than they might otherwise.

Uncertainty

Through stock assessments, scientists aim to determine a numerical value for parameters such as stock size and fishing mortality rate. That value is called a **point estimate.** Discussions of stock assessments can give the impression that when an assessment model produces a point estimate (for, say, the current stock size), the modeler has strong confidence that the particular value is the “true” state of the stock. In reality, point estimates are simply the most likely values. In fact, a wide range of values and alternative models may exist. Those other values or models may explain the data just as well.

In order to make sense of the range of possible values, assessment models produce an estimate of the uncertainty about these values. Often, uncertainty is simply stated as a range within which the true value may lie. That range is called a **confidence interval** or **confidence bound.**

The wider the confidence interval, the more uncertainty exists about where the true value lies. For example, a stock assessment might determine that the current year's biomass equals 100,000 metric tons (the point estimate) with a 95 percent confidence interval of 80,000-120,000 metric tons. In other words, the most likely value for biomass is 100,000 metric tons, but we can be 95 percent sure that the true estimate lies somewhere between 80,000 and 120,000 metric tons.

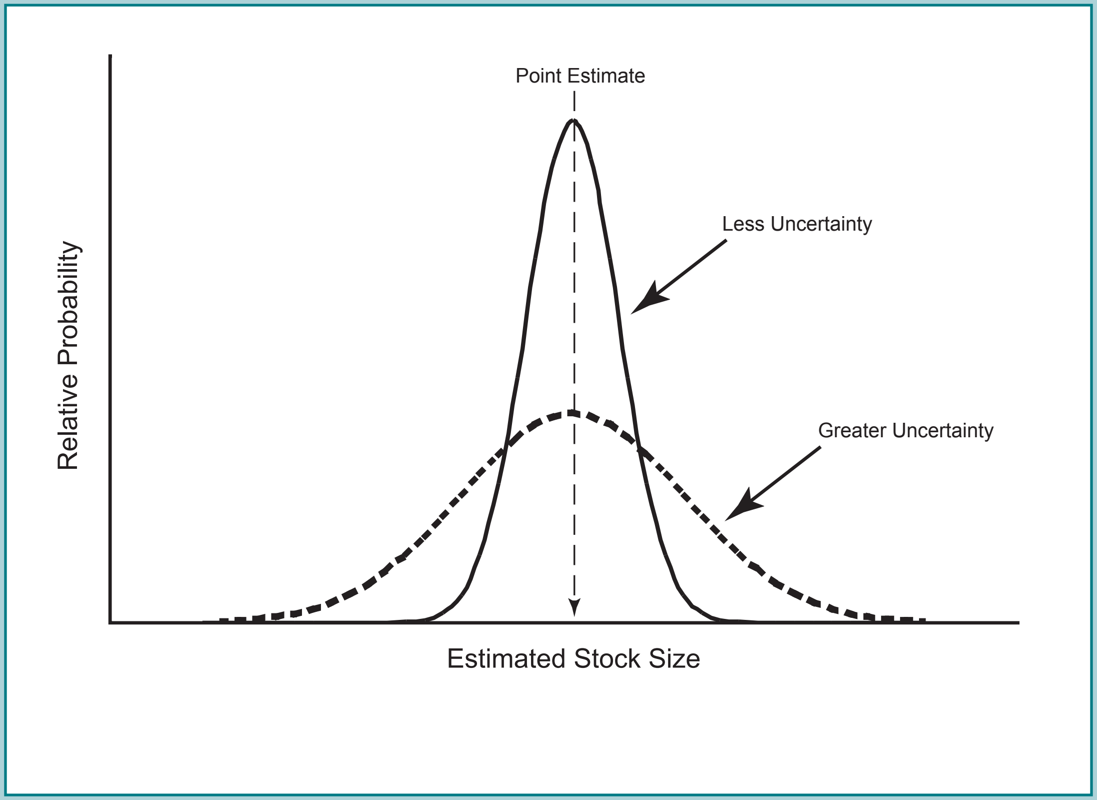
Another approach to estimating uncertainty produces values, called **posterior distributions,** that actually estimate the relative probability of a value being the true value. These distributions are defined by the relative height of the curve. Wide or flat posterior distributions indicate greater uncertainties than do narrow or steep distributions. (See ***Comparing Uncertainty***, right.)

Uncertainty has many sources. Different models allow these uncertainties to affect the outputs in different ways. There is a fine line when dealing with uncertainty. Ignoring too many uncertainties will lead to decision makers putting too much confidence in the output and possibly making poor management choices. On the other hand, incorporating all the uncertainties will likely lead to outputs that are too muddled to give managers useful information.

Uncertainty often exists in the information being input into a stock assessment model. What is the true natural mortality rate? Are catches fully accounted for or might some be

Comparing Uncertainty

The two curves in this graph have the same estimated value, or point estimate, for the stock size (the peak of the curve). However, the two estimates have very different levels of uncertainty. The steeper curve has a high probability that the point estimate is the true value, and the range of possible values is tighter. In the flatter curve, there is a lower probability that the point estimate is the true value.



missing? Are there errors in the way a fish's age or weight is estimated based on its length? Are fish migrating into or out of the stock? Other uncertainties arise from the choice of stock assessment model. Is there a relationship between stock size and recruitment? Does a fish's vulnerability to the fishing gear change each year? Does natural mortality vary from year to year?

No model can fit the data perfectly because no model can possibly capture the true complexity of the system. The goal is to capture the general trends as accurately as possible. Some statistical or estimation uncertainty is inevitable. A number of point estimate values may be equally defendable from a statistical standpoint, due to the nature of the data and the complexity of the models.

Estimating uncertainty allows decision makers to get a handle on how accurate the point values may be, and allows them to choose their actions appropriately. For example, consider two distinct cod stocks with the same biomass threshold. (See ***Uncertainty and Biomass***, left.)

The stocks share the same point estimate for the current size of the stock, but have very different levels of uncertainty. We are much

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less certain about the true status of the stock with greater uncertainty. A stock with greater uncertainty has much more of its curve to the left of the biomass threshold than the stock with less uncertainty. In other words, there is larger probability that the true stock size is below the biomass threshold for the stock with the greater uncertainty.

Would you manage these two stocks in an identical manner? Probably not. In this case, fishing both stocks at the same level has a greater likelihood of causat t8 other wor bably ⊠Aith the

Population Dynamics Models: The Underpinnings of Stock Assessment Models

The Basic Population

that some percentage of the fish will die. If they have estimates of the initial population size and the percentages of fish that will die and recruits that will survive, they can calculate the population size for each year in the future.

This initial formula assumes that a fixed number of fish are born and survive to be counted each year. But it may be more accurate to assume that each reproductively mature fish produces, on average, a fixed number of offspring that survive to be counted. This is known as net fecundity. While **fecundity** can be defined as the number of offspring produced by an individual, **net fecundity** is the number of recruits (offspring that survive to be counted or caught) produced by an individual.

If the net fecundity rate is greater than the mortality rate, the stock will grow larger over time. If net fecundity equals mortality, the stock will remain at a constant level. But if the net fecundity falls below the mortality rate, the stock will eventually shrink to zero. The relationship between the net fecundity rate and the mortality rate is called the **growth rate** for the stock. If the mortality rate is 20 percent per year and the net fecundity rate is 25 percent, the stock will increase at a rate of five percent; the growth rate is equal to five percent.

Because the growth rate is given as a percentage, it does not depend on the abundance, or density, of individuals. The growth rate is therefore categorized as **density-independent.** The density-independent growth rate is also called the **intrinsic growth rate**. The stock will grow or shrink at the same rate, regardless of the size of the stock. These dynamics may apply to stocks at small abundance levels or over short periods of time. However, the intrinsic growth rate model doesn't provide very realistic dynamics for longer-term modeling, let alone projections of future conditions.

A more realistic model assumes that there is some limit to the size of the stock. At some point, due to habitat limitations, the availability of prey, or the presence of predators, a stock will reach an upper limit. This limit is called the **carrying capacity**. Unlike density-independent models, **density-dependent** models assume that the growth rate for a stock is directly related to how close the stock is to reaching its carrying capacity.

At very small stock sizes, the growth rate is unaffected by density-dependent forces and is equal to the intrinsic growth rate. As the stock moves closer to its carrying capacity, the mortality rate will increase or the net fecundity rate will decrease. The result is a decrease in the growth rate.

For most fisheries, it is assumed that density dependence appears most prominently as a change in the net fecundity rate. This is discussed more specifically in the stock-recruitment section on page 26. The basic population dynamics model treats the intrinsic growth rate as a single parameter and doesn't try to model the birth and death processes separately. Different models describe the specific ways in which the growth rate changes with increasing stock size. Each of those models will have different implications for the values of maximum sustainable yield.

The basic population dynamics model discussed in this section is the infrastructure upon which most stock assessment models are built. More complex equations are often added to the basic model to improve its accuracy, but the general principles remain the same.

Stock assessment modelers essentially try to estimate values for mortality rate, the number of recruits, and the initial population size, such that the predicted population size follows whatever trends exist in the data.

Instantaneous Mortality Rates

The total instantaneous mortality rate (*Z*) equals the instantaneous natural mortality rate (*M*) plus the instantaneous fishing mortality rate (*F*). If scientists have estimates for *M* and *F*, they can calculate both annual mortality and annual survival using a table such as the one below.

Total Inst. Mortality Rate (Z)	Annual Survival Rate	Annual Mortality Rate
0.0	100 %	0.0 %
0.1	90.5 %	9.5 %
0.2	81.9 %	18.1 %
0.3	74.1 %	25.9 %
0.4	67.0 %	33.0 %
0.5	60.7 %	39.3 %
0.6	54.9 %	45.1 %
0.7	49.7 %	50.3 %
0.8	44.9 %	55.1 %
0.9	40.7 %	59.3 %
1.0	36.8 %	63.2 %
1.5	22.3 %	77.7 %
2.0	13.5 %	86.5 %
2.5	8.2 %	91.8 %
3.0	5.0 %	95.0 %

constantly throughout the year. Essentially, a small portion of the population is dying each day, each hour, each minute, each second. The instantaneous mortality is the rate at which the population is shrinking in each one of these tiny periods of time.

For mathematical purposes, the instantaneous mortality rate (*Z*) is converted into an annual survival rate. The table in ***Instantaneous Mortality Rates*** (left) shows the relationship between survival rate values and the instantaneous mortality rate.

Of course, not all mortality is due to fishing. The instantaneous mortality rate is actually the combination of the instantaneous *natural* mortality rate (*M*) and the instantaneous *fishing* mortality rate (*F*). When scientists and managers talk about mortality in a management context (that is, fishing mortality rate thresholds and targets), the instantaneous fishing mortality rate (*F*) is the rate to which they are referring. The table at left can also be used to convert *M* and *F* to annual mortality rates. For example, an *F* of 0.2 means that 18.1 percent of the stock dies due to fishing.

Adding Complexity: Age Structure

The basic population dynamics model assumes that mortality, both natural and fishing-related, affects all fish equally. In reality, of course, fish of different ages experience different rates of mortality. When appropriate data, such as valid length-age keys, are available, modelers often add complexity to the basic model by separating the population into age classes. In an age-structured model, separate mortality rates exist for each age class, and the number of recruits is only relevant to the first age class. (See ***Age Structure***, page 24.)

Rather than build a model out to some maximum age (and thus assume all fish die after they reach that age), modelers often include what they call a **plus group**. The plus group contains all fish of a certain age and older. For example, a species may be separated into classes such as age-0, age-1, age-2 and age-3+. In this case, to calculate the size of next year's plus group (3+), modelers multiply the number of this year's age-3+ individuals by the survival rate for that class, then add to that the number of age-2 individuals expected to survive to next year.

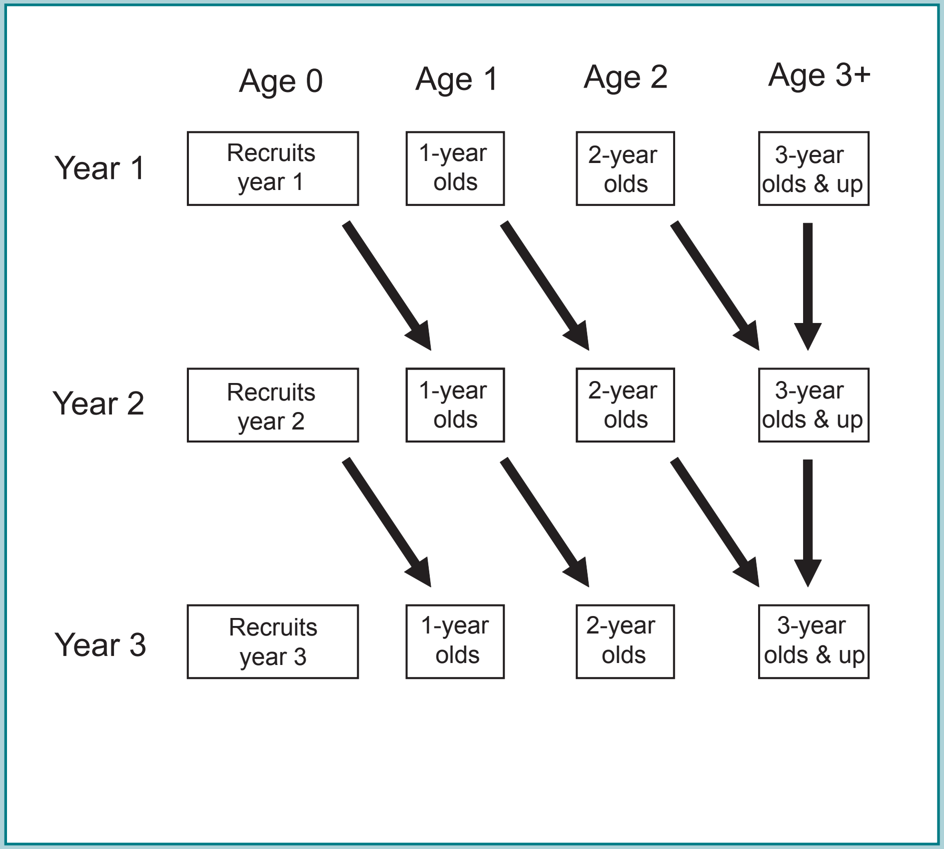
Scientists typically define a plus group based on their ability to predict age from length (which can become more difficult with older fish whose length may not be changing much over time), or based on the age above which very few individuals appear in the data set.

As was the case when we were looking at just the basic population dynamics model, the mortality rate in age-structured models is typically transformed into instantaneous mortality rates. Both fishing mortality rates and natural mortality rates may be different for different ages. Fish of a certain size (or age) may be more susceptible to a particular fishing gear, for example, or they may be more vulnerable to predators.

The pattern of instantaneous fishing mortality rates across ages is called the **partial recruit-**

Age Structure

This diagram illustrates an age-structured population dynamics model, with a plus-group that starts at age 3. The plus group contains all fish age 3 and older.



ment pattern. When the older age classes have the highest instantaneous fishing mortality rates and these rates are relatively constant across these older age classes, the partial recruitment pattern is referred to as "flat-topped." When the intermediate age classes have the highest instantaneous fishing mortality rates and these rates decrease for younger and older fish, the partial recruitment pattern is referred to as "dome-shaped." (See ***Partial Recruitment***, page 25.)

When different instantaneous fishing mortality rates are calculated for each age, stock assessment models will occasionally use what is called the **separability assumption**. Modelers assume that the instantaneous fishing mortality rate for a specific age class in a specific year can be separated into two parts: gear selectivity and instantaneous fishing mortality rate for the fully selected age classes.

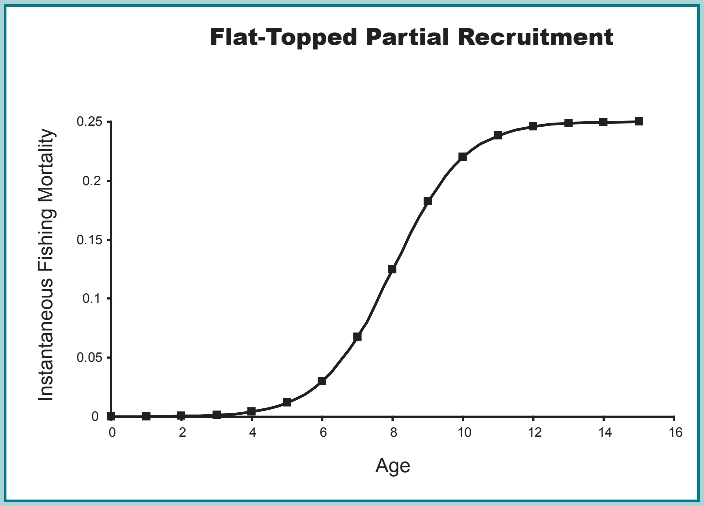
Gear selectivity is the probability that a fish of a certain age or size will be captured by a given gear. The term "fully selected" implies that 100 percent of the fish that encounter a given gear are caught by that gear.

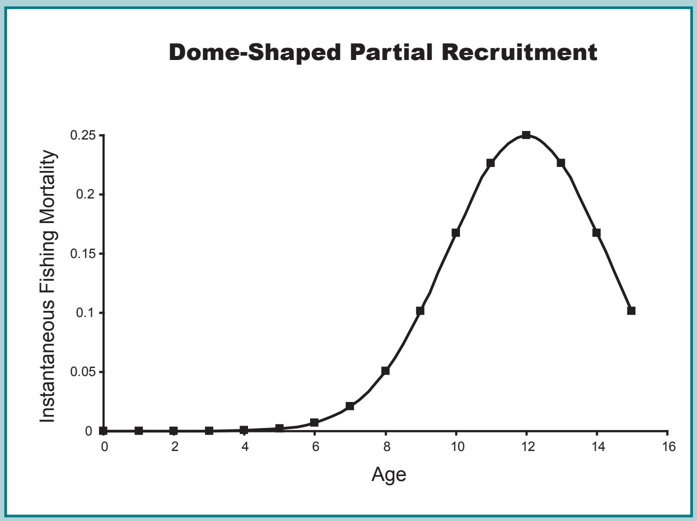
Fully selected age classes have a selectivity value of 1.0, meaning that when fish of that age encounters the gear (whether it be a net, hook, pot, etc.), it will be caught 100 percent of the time and will experience 100 percent of the fully selected instantaneous fishing mortality.

If an age class has a selectivity of 0.25, a fish of that age that encounters the gear will only be caught 25 percent of the time, and that age class would experience only 25 percent of the fully selected instantaneous fishing mortality. When multiple fisheries target a single stock, each

Partial Recruitment

"Flat-topped" partial-recruitment patterns occur when the older age classes have the highest instantaneous fishing mortality rates and the rates are relatively constant across the older age classes. "Dome-shaped" partial-recruitment patterns occur when the intermediate age classes have the highest instantaneous fishing mortality rates and the rates decrease for ages above and below the intermediate ages.





fishery has its own selectivity pattern, which will lead to each fishery having different age-specific instantaneous fishing mortality rates.

The term $\mathbf{L_{50}}$ is occasionally used to denote the length at which a fish has a 50 percent probability of being retained by the gear if it encounters the gear. This should not be confused with the L_{50} that refers to the length at maturity discussed later.

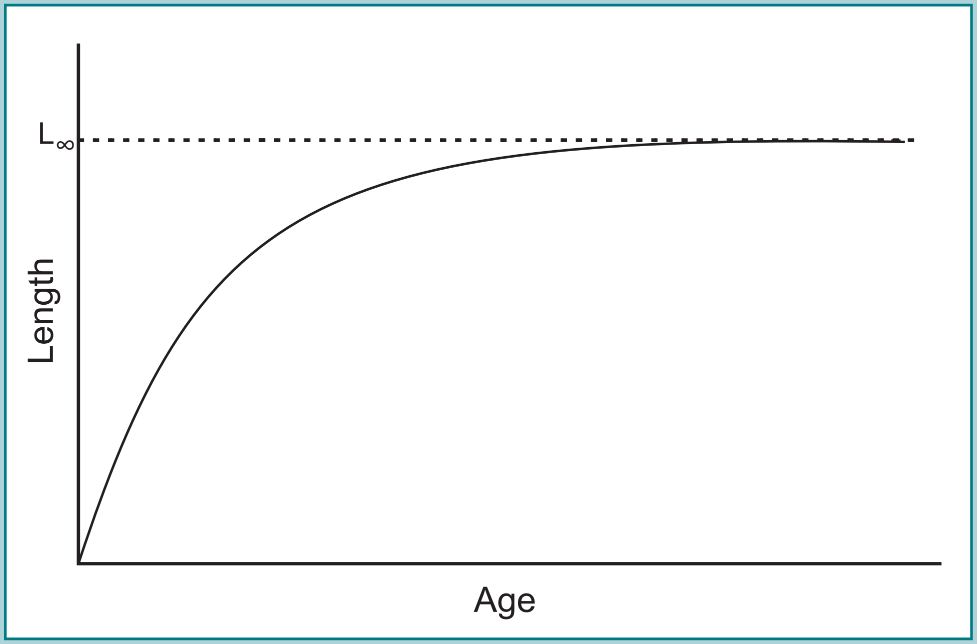
In order to actually use an age-structured model, scientists must be able to separate the fishery-dependent and fishery-independent data into age classes. This exercise can be undertaken as a separate analysis, external to the basic stock assessment model, or it can be incorporated directly into the stock assessment model.

When incorporating age structure externally, scientists generally rely on the length-age keys mentioned previously. When both age and length data are taken from the same fish, scientists can estimate what percentage of fish of a given length fall into each age class. Imagine a species in which 10 percent of nine-inch individuals are age one, 70 percent are age two and 20 percent are age three. If a fishery caught 1,000 fish that were nine inches long, we would classify 100 of them as age one, 700 as age two, and 200 as age three.

This catch-at-age data is incorporated as a direct input into the basic stock assessment model. Performing this analysis outside of the basic stock assessment model typically ignores the uncertainty inherent in the process, however. Therefore, incorporating age structure externally often overestimates the degree of certainty in the results.

Classic Growth Model

The Ludwig von Bertalanffy model is the classic model for predicting how a fish grows as it ages. The LVB model assumes that fish grow most quickly when they are young. Growth slows gradually as the individual gets older, and eventually stops. The size at which the fish stop growing is referred to as "L infinity" (L_∞).



Another approach to age-structured models is to incorporate a growth model directly into the stock assessment model. The classic growth model was developed by Ludwig von Bertalanffy and is referred to as the **von Bertalanffy growth model** or the **LVB growth model**. The LVB model assumes that growth occurs most quickly at the youngest ages, slows gradually as the fish gets older, and eventually levels off. The size at which growth levels off is referred to as "L_∞" (or "L-infinity"). (See ***Classic Growth Model***, left.)

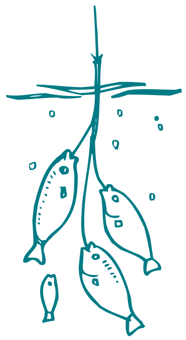
By estimating this growth model within the stock assessment model, the uncertainty in age associated with each size is passed through the model, which produces a more realistic estimate of uncertainty in the output.

Some stock assessment models completely avoid the problems of converting length to age by modeling the population dynamics solely on length. These models are called length-based stock assessment models. They are less commonly used, however, due in large part to their complexity.

Adding Complexity: Stock-Recruitment Functions

The models described to this point do not take into account the potential relationship between the number of recruits and the number of reproductively mature individuals in the population.

Some stock assessment models maintain the assumption that no such relationship exists, and attempt to estimate an average level of recruitment or a level of recruitment that changes from year to year. Other models add complexity by attempting to define, in mathematical terms, how the number of reproductively mature adults in a stock will relate to the number of recruits in that stock the following years.



In order to use a formal stock-recruitment relationship, modelers must estimate the number of reproductively mature adults. In a model that has not been adjusted for age, scientists often assume that some fixed percentage of the population is reproductively mature.

In an age-structured model, scientists use a **maturity ogive** determined from other studies. The maturity ogive is the percentage of mature individuals in each age class. Scientists use the term L_{50} to refer to the median length at maturity: half of the mature individuals in a population first attain maturity at a length longer than L_{50} and half at a length shorter than L_{50}. This length, L_{50}, is sometimes used by managers to set the size limits in a fishery.

When reading management documents, one must pay attention to context to determine whether L_{50} refers to maturity or to selectivity, as described earlier.

The simplest form of the mathematical relationship between recruits and mature fish is to assume that each mature fish produces, on average, a fixed number of offspring that survive to be counted. This is the approach presented in the basic population dynamics model to describe the density-independent intrinsic growth rate. More complicated functions allow for the number of recruits to be a density-dependent function of the number of reproductively mature individuals.

A variety of density-dependent functions can be used to describe a stock-recruitment relationship. The two most common are the Beverton-Holt model and the Ricker model. (See ***Stock-Recruitment Relationships***, right.)

The Beverton-Holt model assumes that the number of recruits increases as the size of the reproductively mature population increases, up to a point. Above that point, the number of recruits holds constant even as the reproductively mature population increases, because the habitat simply cannot support any more recruits. This pattern is known as **perfect compensation.**

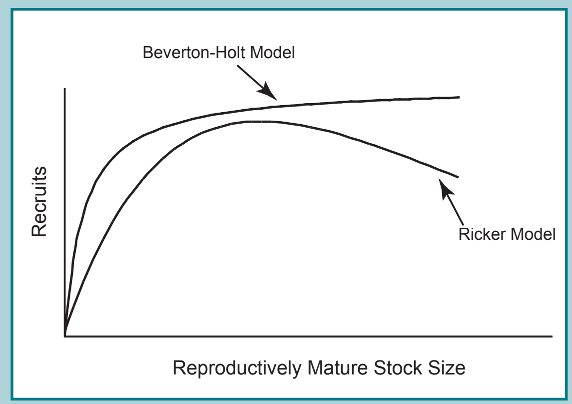
The Ricker model differs in that it assumes that, rather than remain constant, the number of recruits actually starts to decrease when the reproductively mature population is large. This process is called **overcompensation.**

What happens on the other end of the spectrum, when the reproductively mature population is small? A process called **depensation** may kick in. Depensation occurs when net fecundity decreases as the reproductively mature population decreases. In other words, as the reproductively mature population gets smaller, fewer recruits per adult make it into the stock.

Stock-Recruitment Relationships

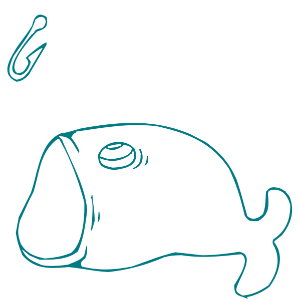
Stock-recruitment models are used to define the relationship between the number of reproductively mature adults and the number of recruits in a stock. The two most common stock-recruitment models are the Beverton-Holt model and the Ricker model.

The Beverton-Holt model assumes that the number of recruits increases as the mature population gets larger, then levels off. The Ricker model assumes that when the reproductively mature population reaches a certain level, the number of recruits actually decreases rather than remaining constant.



One form of depensation is the **allee effect,** in which fertilization rates drop as the population decreases – as mature fish have more difficulty finding mates, for example. The result is fewer recruits born per reproductively mature individual. The result of depensation is that it takes longer for a stock to recover from a small population size – if it can recover at all.

Some scientists argue that because so many factors are involved in the stock-recruitment process, it's better to treat them as purely mathematical concepts than to try to infer the specific biological causes behind them. In other words, they believe the data should determine which model is most appropriate. Unfortunately, the available data often do not give much insight into this determination. In that case, scientists must test the sensitivity of the stock assessment outputs (such as biomass or fishing mortality rates) to their assumptions about the specific stock-recruitment relationship.



Adding Complexity: Weight and Biomass

The basic population dynamics model deals with the number of individual fish in a stock, either as an entire group or categorized by age. But managers sometimes wish to focus instead on the stock's biomass, the total weight of all the fish in the stock.

The most straightforward way to estimate biomass is to calculate the average weight of an individual fish, either for each age class or for the stock as a whole, and then multiply that average weight by the number of individuals in the class or stock.

Rather than focusing on the number of fish, scientists sometimes focus on biomass, the total weight of all the fish in a stock.

For some modeling approaches, the average weights for each age class, known as the "weights at age," are estimated directly from surveys. To calculate the total biomass, the average weight is simply multiplied by the number of individuals, either in each age class or in the stock as a whole. No special weight-related dynamics are involved in this type of biomass calculation. The stock assessment is still driven by numbers, and the numbers are simply converted into weight.

In most instances, the estimates of average weight at age are derived from data originally collected as length and weight. The average weight for a given length classes is then converted to an average weight for a given age, based on length-age keys.

Of course, a range of weights and ages exist for each length class. The numbers you see in a table of average weight at age may actually contain a great deal of uncertainty that is rarely discussed. The ways in which a modeler generates these average weight-at-age tables will vary from stock to stock and modeler to modeler.

Another approach to incorporating biomass builds on the use of the LVB model to separate the total number of individuals into age classes according to their length. This approach relies on data from sampled fish and employs a mathematical function to convert length to weight.

In this method, the uncertainties in weight associated with a given length are passed through the model into the final results. Assuming the appropriate models are used, this approach will give more realistic estimates of the uncertainty associated with the various biomass targets and thresholds.

Applying Stock Assessment Models to Data

5

Indices of Abundance

Estimates of catch typically make up the bulk of the data that is applied to a stock assessment model. But most stock assessment models also require some kind of **index of abundance**. The index of abundance is a value that indicates the trend in *relative* abundance over time.

Often an index of abundance is simply the number of fish caught during a survey. The index of abundance for a cod stock, for example, may be the average number of cod caught per tow from a research vessel. Each tow would be of a specified length, depth and speed using a standardized net, so that the index of abundance values could be compared over time.

For example, an index could say that a stock increased by five percent between one year and the next. The index of abundance alone cannot tell managers whether this means the stock increased from 100,000 tons to 105,000 tons or from 100 million tons to 105 million tons. Other data, such as landings records, are required to translate the relative change observed in the index (the percentage change) to absolute change (in terms of number of fish or biomass).

The primary – and crucial – assumption behind the index of abundance is that changes in the index are proportional to changes in the actual stock abundance, and vice versa. Essentially, though not quite this simply, if the index drops by 10 percent we assume the stock abundance has dropped by 10 percent. Conversely, if the stock abundance decreases by 10 percent, our observed index must decrease by 10 percent as well.

A more mathematically formal way of stating this is that the index of abundance is consistently proportional to the true stock size or biomass. This proportionality will not change over time or as the stock size changes; the value, therefore, is known as the **proportionality constant**. The true population size (which will be estimated by the stock assessment model) equals the index of abundance multiplied by this proportionality constant. Modelers may use more complex models to relax this assumption.

The proportionality estimate is a very important property of indices of abundance. The index of abundance itself only provides information on *relative change*. (See ***Relative Change***, page 30.)

Two valid indices may exist, and one may be, say, 10 times as large as the other. Yet because they are estimating the relative change in the stock over time, both indices provide identical information to the stock assessment. The 10-fold difference in the number of fish captured by the survey will be evident in estimates of the proportionality constant.

The scale of the proportionality constant will be determined mostly by data other than

Relative Change

The population size is equal to the index of abundance multiplied by the proportionality constant. An index of abundance is typically just the number of fish caught in a standardized survey. One survey may collect 18 groundfish and another might collect 180. But both indices are valid. As long as the surveys are performed consistently year to year, either index will provide the same information to the stock assessment because both provide information on relative change.

Year	Index of Abundance 1 (Actual Value)	Percent Increase over last year	Index of Abundance 2 (Actual Value)	Percent Increase over last year
1	10	—	100	—
2	12	20%	120	20%
3	14	17%	140	17%
4	16	14%	160	14%
5	18	13%	180	13%
6	20	11%	200	11%
7	22	10%	220	10%
8	24	9%	240	9%
9	26	8%	260	8%
10	28	8%	280	8%

the index itself. One of the main keys to producing a reliable index of abundance is consistency, regardless of how many more fish one index contains than another index.

Catch-per-Unit Effort

The majority of indices of abundance used in stock assessments are derived from estimates of **catch-per-unit effort,** the number or biomass of fish caught as a function of effort. Catch-per-unit effort estimates may come from either fishery-dependent or fishery-independent data.

Unfortunately, in relying on catch-per-unit effort estimates, scientists can run into conditions that violate the proportionality assumption described in the previous section. Fishery-dependent catch-per-unit effort estimates can violate this assumption, mostly because fishermen will actively seek out areas with greater fish concentrations. As a result, their catch-per-unit effort could remain stable in the face of a declining stock.

Consider a stock that contracts its range as the population shrinks, or increases its range as the population grows. Despite the changing range, catch-per-unit effort may remain relatively constant if the fishermen focus their effort on the center of the range, where fish density remains relatively stable.

The opposite may occur if a stock is comprised of local populations that are reluctant to move. In that case, catch-per-unit effort can decline dramatically as one local population is fished down, despite the fact that abundance over the entire region may be relatively stable.

The reliability of fishery-dependant catch-per-unit effort estimates is also affected by changes in technology. Technological advances, such as gear improvements, fish-finding ability and changes in the number of people or fish a vessel can hold, can cause the definition of "effort" to change over time. That can change the relationship between catch-per-unit effort and abundance.

When catch-per-unit effort estimates are produced from fishery-independent surveys, catch is typically defined by survey results and effort is defined by sampling design. Surveys can be designed to avoid many of the pitfalls of fishery-dependent catch-per-unit effort (such as by using standardized gear).

By sampling across the fish's entire potential range, scientists can detect range contraction or expansion. The catch-per-unit effort estimates will therefore be less sensitive to localized depletion. Standardizing the sampling method helps ensure that the estimates of catch-per-unit effort are comparable over time.

The true population size equals the index of abundance multiplied by the proportionality constant.

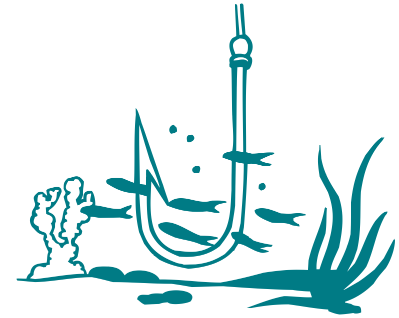
Estimates of Actual Stock Size

In some cases, scientists conduct surveys in an attempt to directly estimate the size of the stock. In these cases, the proportionality constant equals one. In other words, the index of abundance is simply equal to the population size. Scientists often attempt to estimate the size of marine mammal populations directly, using aerial surveys or transect surveys from vessels. One of the key assumptions in this approach is what percentage of the population is actually visible at the time of observation.

Properly calibrated acoustic surveys and tagging or mark-and-recapture studies can also provide direct estimates of stock size. These types of studies are specifically designed to provide stock abundance estimates. They should not be confused with the majority of surveys, which are simply designed to provide indices of abundance.

Scientists occasionally run experiments so that they can convert a more traditional survey into a direct estimate of stock size. Essentially, they create an independent estimate of a survey's proportionality constant by running a "depletion experiment."

In these experiments, scientists run a given gear across the same area over and over again, until the catch rate is zero (that is, there's nothing left) or until the catch rate stops decreasing. Based on the information from this experiment, scientists can estimate the proportionality constant, which can, in turn, be applied to a survey to estimate total population size.



Index-Only Models

In data-poor environments, especially when estimates of catch are unreliable or when the species' biology is poorly understood or sufficiently complex, managers may choose to govern the stock based on an **index-only model.** An index-only approach does not attempt to model the dynamics of the stock, predict the stock's response to management, or even assess the fishery relative to its maximum sustainable yield. Rather, index-only approaches attempt to maintain the index of abundance within a certain range, restricting fishing when the index falls below the range and loosening restrictions as the index rises above the range.

For an index-only model to succeed, the stock must be relatively resilient and decision makers must choose an appropriate index. If the index does not track the stock well, it could give incorrect indications of changes in stock abundance.

If stock abundance fluctuates wildly due to changing environmental conditions, or is very sensitive to minor changes in fishing practices, an index-only model will be extremely difficult to implement successfully. In such a case, the risks of fishing the stock too hard would be high. Managers would have to expect the fishing community to dramatically increase or curtail effort in a short period of time, whenever abundance increased or decreased. Most terrestrial hunting programs, however, use this very approach.

Fitting Models to Data

Whether a stock assessment scientist uses a simple biomass dynamics model or a complex age-structured model with stock-recruitment and growth equations, he or she must fit the model to data. To do so, the scientist examines a series of equations that are meant to represent the true stock dynamics. None of these equations will be exact descriptions of the biological processes, but some will represent the dynamics better than others.

By estimating values for parameters such as the number of recruits per year, the starting size of the stock, and survival rate, the scientist can produce an estimated stock size for each year.

Scientists compare the estimated stock sizes to the index of abundance, which is assumed to be proportional to the true stock size. The proportionality constant becomes an additional parameter to be solved. The first goal of model fitting is to find values for the parameters that come closest to matching the index of abundance.

There are a variety of ways to define "closest." How well a model fits the data is known as its **goodness of fit**. Stock assessment modelers use a wide variety of computer programs that automatically determine which values for the parameters produce predictions that best fit the data.

The basic approach of each is essentially the same. The programs predict the stock sizes using initial values for parameters such as survival rate and number of recruits. They then compare the predictions to the observed data, changing the values of the parameters to move the predictions closer to the observed data until the predicted values cannot get any closer to the observed values. (See ***Goodness of Fit***, page 33.)

One goal of model fitting is to examine how sensitive the model is to changes. How does the predicted stock size change when the model is simplified or made more complex? Statistical measures exist to determine whether an improvement in goodness-of-fit is worth increasing the complexity of the model.

Regardless of whether the complexity is worthwhile from a statistical sense, the modeler should still explore how sensitive the predicted outputs are to the choice of model. Even if adding complexity to the model only improves fit by a small amount, it's important to know how that change might affect estimates of a stock's status relative to its targets and thresholds.

For readers who are interested in learning more about fitting models to data, we recommend ***The Ecological Detective*** by Ray Hilborn and Marc Mangel (Princeton University Press, 1997).

Frequentist versus Bayesian Approaches

One important question in modeling is how to incorporate preexisting knowledge into the model. We will not go into the specifics of these approaches, but present them here in a very general context so that the reader will be familiar with these terms when they are mentioned in a stock assessment. Most stock assessment models take the ***frequentist*** approach, but do not specifically state this. When a stock assessment takes a ***Bayesian*** approach, it is usually stated explicitly.

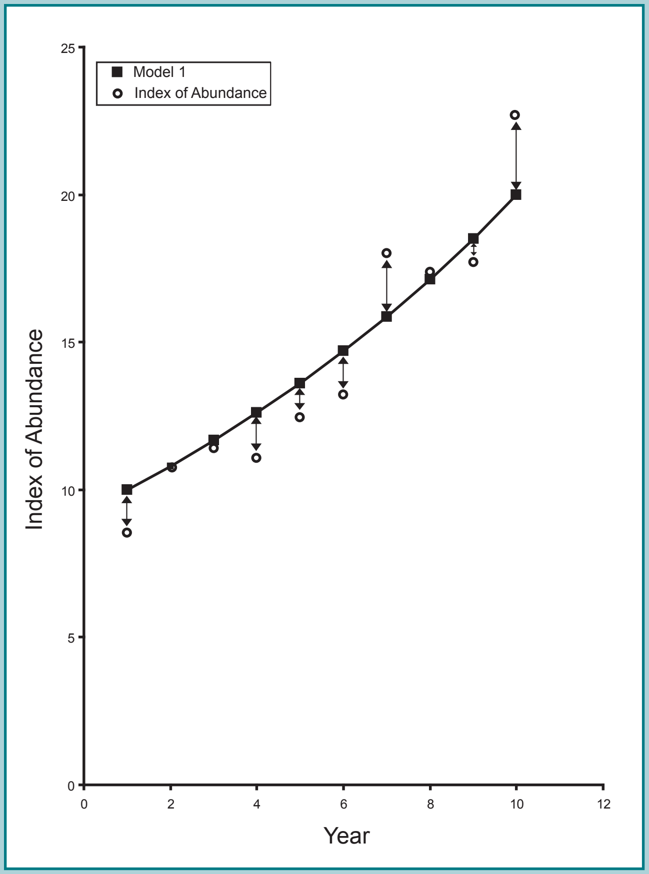
The frequentist approach uses only data currently on hand. For those parameters for which the modeler has no data, he or she will make strict assumptions. For example, if the natural mortality rate for the assessed species is unknown, the modeler may choose to substitute the mortality rate for a closely related species instead. The uncertainty in that value will not be directly incorporated into the results, but the modeler will test how sensitive the model is to the use of that value.

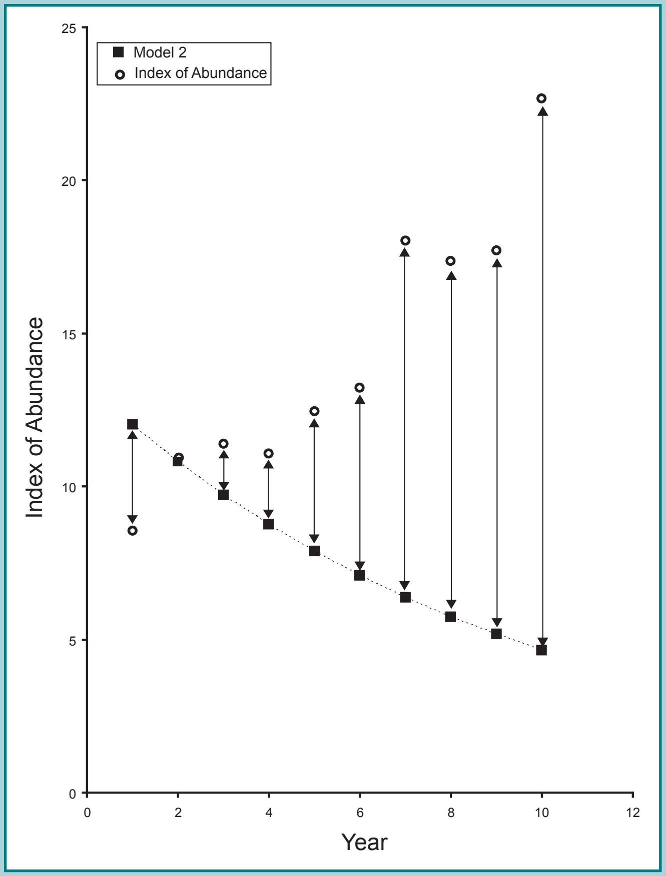
In this case, sensitivity tests would involve repeating the model calculations several times,

Goodness of Fit

Whether scientists use very basic or very complex models, they must fit their model to the available data. To do so, they must find values for the various parameters (such as stock size and fishing mortality rate) that best match the observed index of abundance. Stock assessment modelers use a variety of computer programs to determine which values produce predictions that best fit the data.

The two graphs shown here illustrate two different models for a single stock. In Model 1, the difference between the squares (the model's predicted stock size) and the circles (the index of abundance) is small. In Model 2, the difference between the predictions and the actual index of abundance is much larger. Therefore Model 1 is a better fit for the data.





using slightly different values for the natural mortality each time. Scientists then examine the degree to which changing those values has changed the outputs (biomass and fishing mortality rates).

The Bayesian approach takes the opposite perspective. In this approach, modelers assume preexisting knowledge about all of the parameters in the model and explicitly define relative levels of certainty for each of those values. How certain is the value for natural mortality, for example? For the number of recruits? These explicit definitions are call **priors**, as in prior knowledge.

Vague priors allow for a very wide range of values and don't give any one value much more importance than the others. This allows modelers to directly incorporate information from other related species or results from other experiments in a formal, rigorous way. The uncertainty in these values will be passed directly through to the results. Models that take the Bayesian approach must clearly explain where the prior information comes from and how the priors were decided upon. Scientists should also test the model's sensitivity to changes in the priors.

Biomass Dynamics Models – Theory

Scientists use biomass dynamics models, also called production models, in an attempt to apply the basic population dynamics model to data on catch. This type of model is most often used when scientists are not able to sort the total catch into age classes, either because of a lack of length data or a poorly defined length-age key. However, it is often useful to compare the outputs from a biomass dynamics model to those from an age-structured model to explore how sensitive the outcomes are to the model structure when such aging data does exist.

The two dominant variables for biomass dynamics models are carrying capacity and the intrinsic growth rate (the growth rate when density-dependence does not play a role).

Unfortunately, it's very difficult to predict either of these parameters accurately unless the stock size has been at very high levels (approaching carrying capacity) or, in the case of intrinsic growth rate, at very low levels.

Scientists often make references to a stock making a "one-way" or a "two-way" trip. A one-way trip means that scientists have made observations while the stock was either fished down from high abundance or has grown from very low abundance, but not both. A two-way trip indicates that the stock has been observed at both high and low abundance.

One-way trips can provide information on either carrying capacity (when fished down from high abundance) or the intrinsic growth rate (when grown up from low abundance). Yet even when the stock has been observed while being fished down, there's rarely good information about just how close the stock came to reaching the actual carrying capacity. The estimated carrying capacity from a one-way trip will always underestimate the true carrying capacity and will often contain a great deal of uncertainty.

Two-way trips tend to provide more reliable estimates of both carrying capacity and the intrinsic growth rate than either of the one-way trips does on its own. Essentially, the greater the contrast in stock sizes over time, the more reliable the estimated parameters.

such as the Pella-Tomlinson model, are somewhat more flexible, because they add parameters to describe how the growth rate changes with respect to stock size. But the values for targets and thresholds in the Pella-Tomlinson model are no less sensitive to errors and biases in carrying capacity or intrinsic growth rate than the more common density-dependent models.

Age-Structured Models – Theory

As the name implies, age-structured models add information about age to the basic population dynamics model. Age-structured models may or may not include a stock-recruitment function. They do, however, separate instantaneous total mortality into natural mortality and fishing-related mortality.

Obviously, age-structured models require that catch be divided into age classes. Age-specific indices of abundance are very helpful in model fitting, but are not vital. In fact, some of these models can even be fit without any index of abundance whatsoever (although it's not recommended).

Age-structured models are categorized based on how they link the population dynamics equations to the data. **Forward-projecting** models start with an initial population in the past that then moves forward in time. **Backward-projecting** models (also called hindcasting models) start with the current population and work backwards.

To figure out how many fish were present at the beginning of last year using a backward-projecting model, scientists start with the stock size at the beginning of this year, add back those fish that died during the past year, and subtract those that were born.

A backward-projecting approach is also applied to the way in which age structure is incorporated. In a backward-projecting model, the arrows in the diagram shown in ***Age Structure*** (page 24) would simply be reversed. Another way of categorizing age-structured stock assessment models is based on whether or not the model treats the catch-at-age as being known exactly ("given") or not ("fit").

Forward-projecting models begin by looking at some population in the past and then work forward through time.

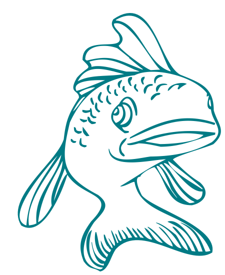
Virtual population analyses (VPA) are a common type of age-structured population dynamics model. Virtual population analysis models are usually backward-projecting (though occasionally forward-projecting) models that treat catch as "given," or known exactly.

Virtual population analysis models are most often used in the frequentist approach, in which scientists use only data that's currently on hand and make strict assumptions about parameters for which no data exists. The program ADAPT is the most commonly used backward-projecting virtual population analysis model.

Because virtual population analysis models use age-specific catch data that is assumed to be without errors, scientists know (or assume they know) exactly how many four-year-olds were caught this year, how many three-year-olds were caught last year, two-year-olds caught the year before that, etc. This allows scientists to track any cohort of fish back in time with relative ease.

Tracking **completed cohorts** is fairly straightforward. Completed cohorts are those born so long ago that none of the fish could possibly remain alive in the current stock. If the scientist knows natural mortality, he can work backwards from the number of fish caught in the oldest age group to obtain values of stock size and instantaneous fishing mortality for each age class. He can do so through algebra alone, with no statistics or model-fitting necessary.

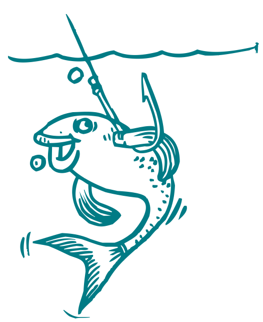
The problem is trickier for **incomplete cohorts**, those cohorts still in the stock that have not yet reached their maximum age (for example, a five-year-old cohort of a species that has a maximum age of 10). The model must estimate the percentage of each incomplete cohort still remaining in the stock. What percentage of seven-year-olds are still living? Of eight-year-olds?



One way to improve estimates for incomplete cohorts is to incorporate indices of abundance, referred to as tuning indices, into the virtual population analysis. The result is called a "tuned" virtual population analysis.

The model-fitting exercise for a tuned virtual population analysis is essentially the same as the generic model-fitting procedure described above. Backward-projecting virtual population analysis models are quite sensitive to errors in estimates of natural mortality and age. They are also sensitive to estimates of the **terminal F's**, the estimated age-specific instantaneous fishing mortality rates for the incomplete cohorts in the most current year. Backward-projecting virtual population analysis models can have a very difficult time estimating terminal F's, though the use of tuning indices helps enormously.

One way a scientist tests for the model's sensitivity to terminal F's is to perform a **retrospective analysis**: First fit the model treating the current year as the starting point, then refit the model ignoring this year's data and treat last year as the starting point, then refit the model again, ignoring the two most recent years of data and treat three years ago as the starting point, and so on.



Virtual population analysis models are fairly robust for examining historical trends in the fishery.

A scientist examines the estimated stock sizes and instantaneous fishing mortality rates for all years under each of these models. He or she then looks to see if the estimates are changing in any kind of systematic way, called a **retrospective pattern**. For example, a modeler may examine the data to determine how the estimated stock size for certain age classes in 1995 depends on whether the starting year is 2000, 1999, 1998 or 1997.

For estimates of both stock size and instantaneous fishing mortality, sensitivity to the terminal F's decreases with time, but the degree of this decreasing sensitivity depends on the life history of the fish.

In a 2006 assessment, for example, the stock size estimate for the year 1995 will be more sensitive to the terminal F's than the stock size estimate for 1990. This decrease in sensitivity over time is smaller for a very long-lived species (that has many incomplete cohorts still in the stock) than for a very short-lived species (that has few incomplete cohorts still in the stock). This property makes virtual population analysis models fairly robust for examining historical trends in the fishery.

Statistical catch-at-age models take a different approach than do backward-projecting models. Statistical catch-at-age models are almost always forward-projecting models and often treat the catch as data needing to be fit (rather than assumed known without error).

Most statistical catch-at-age models take the Bayesian approach, but this is not required. The stock-synthesis approach developed by Methot, a type of statistical catch-at-age, allows scientists to directly account for errors in aging from length data and uncertainty in the length-weight relationship. The stock-synthesis approach can handle data from a variety of surveys and fisheries, all with their own selectivity curves.

Compared to virtual population analysis models, statistical catch-at-age models use more formalized statistical approaches to link the data to the population dynamics models. The model-fitting exercise for a statistical catch-at-age model is the same as the generic model-fitting procedure. Because of its forward-projecting approach, the stock sizes in the earliest years are the least precise (in contrast to virtual population analyses, in which the stock sizes in the most recent years are least precise).

While statistical catch-at-age approaches are still sensitive to aging errors and to errors in natural mortality, the uncertainty in these parameters can be directly incorporated into the model – if, that is, the modeler has some knowledge about how large those uncertainties might be.

Age-Structured Models – Targets and Thresholds

Estimating targets and thresholds with age-structured population dynamics models is much more difficult than with biomass dynamics models. In biomass dynamics models, target and threshold values could be derived from simple algebra; in an age-structured population dynamics model, the values must be derived through computer simulation.

The final stock assessment model will produce estimates for the stock's natural mortality, growth rate, maturity schedule and selectivity to fishing gear. Using these estimates, the modeler can predict the dynamics of a theoretical cohort under different levels of fishing mortality.

For example, a simulation may start with 1,000 fish born into the stock. To estimate the maximum spawning potential of the stock per recruit, the modeler will grow and age this theoretical cohort with the age-specific instantaneous fishing mortality rate set to zero. As the cohort ages, it will result in a certain amount of mature biomass each year.

Modelers calculate the maximum spawning potential per recruit by adding up the mature biomass from each year and dividing that value by the number of recruits that started out in the cohort.

Scientists often estimate a fishing mortality threshold of $F_{40\%}$, the fishing mortality rate that reduces the spawning stock per recruit to 40 percent of that which would exist in the absence of fishing. To estimate $F_{40\%}$, the modeler will repeatedly run the model with ever-increasing fishing mortality rates until the sum of the mature biomass each year per recruit equals 40 percent of that obtained when fishing mortality was set to zero.

Yield-per-recruit reference points (such as F_{max} and $F_{0.1}$) are calculated in the same fashion. Modelers may start with 1,000 fish born into the stock and grow and age the cohort with the age-specific instantaneous fishing mortality rate set to zero. Since there is no fishing mortality, the yield is zero. Modelers then increase the fully selected instantaneous fishing mortality rate by a very small amount. The cohort will produce a certain amount of yield each year as it grows, ages and gets caught by the fishery.

Adding the yield from each of these years and dividing the value by the number of recruits that start in the cohort will result in one point on the yield-per-recruit curve. (See ***Calculating Fishing Mortality Thresholds***, page 15.)

The modeler will then repeat this process by repeatedly increasing the fully selected fishing mortality rates to generate the full yield-per-recruit curve. Once the curve is generated, he or she can estimate the values of F_{max} and $F_{0.1}$.

As you can see, there is no guarantee that these measures will ensure that the stock can actually replace itself or grow. There is no feedback into recruitment. Essentially, scientists must trust these approaches based on experience, both in the real world and in simulations that have tested the robustness of the approach.

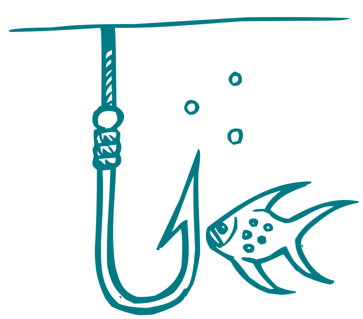
Estimating Uncertainty

One of the primary goals of a stock assessment is to estimate the uncertainty in the status of the stock and in the target and threshold values. A point estimate is of little use if the modeler doesn't know how much confidence to put in it.

One way to examine the uncertainty in a stock assessment is with a **sensitivity analysis**. In nearly all assessments, some parameters (such as natural mortality) are assumed known and fixed. A sensitivity analysis refits the assessment model with different values for the assumed parameters to examine how much, if any, the outputs change.

Sensitivity analyses can also be performed on the functions themselves. For example, modelers could allow recruitment to be estimated by a stock recruitment function (such as Ricker or Beverton-Holt) or could attempt to produce individual recruitment estimates for each year.

In most cases, sensitivity analyses are performed when scientists don't know how much more reliable one assumed value or function is over another. For example, if the modeler doesn't know the natural mortality of the species being assessed, but does have an estimate for a related species, he or she may choose to use that value in the assessment. The modeler would then perform a sensitivity analysis to examine how much the results might change if he raised or lowered that value by, say, five, 15 and 25 percent. He doesn't know which is best, or how much better one might be over another, so he examines the range.



When the modeler can make relative statements about his confidence in the values for the input parameters, he can use Bayesian approaches to directly incorporate this into the assessment and pass the uncertainty through directly to the outputs.

Even if the modeler is absolutely positive about the assumed parameters and functions, uncertainty will still exist in the results. The point estimates produced by the stock assessment model will give the most likely values for a given parameter, but other values may be almost as likely.

One way to estimate the uncertainty is called **bootstrapping**. Bootstrapping is typically used with virtual population analysis models or models using a frequentist approach.

Statistical catch-at-age models, especially those using a Bayesian approach, will often attempt to estimate uncertainty with an approach known as **Markov Chain Monte Carlo**, which results in relative goodness-of-fit estimates for a range of values for all the parameters. One advantage of this approach is that it can directly incorporate prior information about the parameter values and can pass the uncertainty through to the biological reference points and to the estimates of how the stock may respond to future management actions.

Making Recommendations

6

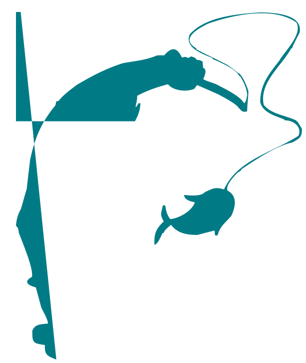
Stock assessments are merely tools. They cannot produce concrete decisions about how to manage a stock. They cannot tell a decision maker which management options are right and which are wrong. Rather, the stock assessment is designed to give managers and decision makers information about the current status of a stock relative to its biological reference points. It provides them with information about how the stock might respond to specific future management actions.

To produce a stock assessment, a scientist has applied appropriate models to the available data, examined the uncertainty in the models' outputs, and tested the sensitivity of the outputs to changes in the underlying assumptions.

The scientist will often make statements about the relative validity of each of the models. He or she may even choose a "preferred" model. Such a preference, however, is based on measures like goodness of fit, accurate reflections of uncertainty, and robustness to changes in assumptions. Preference is not based on the specific outcome of a model with regard to the stock's status.

The stock assessment will rate how likely each management option is to achieve its stated (or mandated) objectives. And a stock assessment should quantify the risk or probability of the option not achieving the goal.

Choosing between management options is ultimately the role of the manager. Ideally, a careful and complete stock assessment will provide the manager with the necessary information to manage the stock successfully into the future.



Glossary

allee effect – a situation in which fertilization rates may decrease in a small population, causing fewer recruits to be born per reproductively mature individual. The result of depensation is that it will take longer for the population to recover from small stock sizes, if it can recover at all, than would be expected for a healthier stock.

assessment model – one of a number of statistical techniques used to conduct a stock assessment.

backward-projecting model – also called *hindcasting* model, an age-structured model that begins with the current population and works backward to estimate past population sizes.

Bayesian approach – a method of incorporating preexisting knowledge into a model by defining the relative levels of certainty about the values of each parameter (called *priors*) in the model. (Contrast with *frequentist approach.*)

biological reference points – quantitative values, often stated in terms of fishing mortality or stock size, that summarize either a desired state for the stock (a target) or a state of the stock that should be avoided (a threshold).

biomass – the total weight of all the fish in the stock.

bootstrapping – a method of estimating uncertainty

bycatch – fish that were not specifically targeted but were inadvertently harvested during the fishing process.

carrying capacity – the maximum upper limit to the size of a stock, determined by the availability of prey, the presence of predators, or other limitations of the habitat.

catch-per-unit effort – the number or biomass of fish caught as a function of fishing effort.

cohort – a group of fish born in the same year.

completed cohorts – those cohorts, or age-classes, born so long ago that it's certain none remain alive in the current stock.

confidence bound – see *confidence interval.*

confidence interval – also called the *confidence bound*, a range of values within which the true value most likely lies.

control rules – directives that guide the ways in which fishing mortality rates are adjusted over time based on stock size.

creel survey – a survey of catch from recreational fishermen, observed by portside observers for size and age data.

decreasing marginal rates of return – occurrence whereby each additional unit of fishing effort produces smaller and smaller increases in yield per recruit.

density-dependent growth rate – growth rate model that assumes the growth rate for a stock is directly related to how close the stock is to reaching its carrying capacity.

density-independent growth rate – see *intrinsic growth rate.*

depensation – a situation in which net fecundity decreases with a decrease in the size of the reproductively mature population.

discards – fish that were thrown back because they were the wrong size, sex or species. All discards are a form of bycatch.

fecundity – the number of offspring produced by an individual.

fishery-dependent data – data derived from the fishing process, through such avenues as self-reporting, onboard observers, portside surveys or telephone surveys.

fishery-independent data – data derived from activities, such as research surveys and some tagging experiments, that do not involve the commercial or recreational harvest of fish.

fishing mortality rate (F) – the rate at which fish are harvested or killed by fishing each year.

fishing mortality threshold ($F_{threshold}$) – also called the *maximum fishing mortality threshold*, the threshold above which a stock is said to be experiencing overfishing.

forward-projecting model – an age-structured model that begins with an initial past population size and moves forward in time to estimate current or future population sizes.

frequentist approach – a method of incorporating preexisting knowledge into a model by using only data currently on hand. (Contrast with *Bayesian approach.*)

fully selected – a situation in which 100 percent of the fish that encounter a particular gear are captured by that gear.

gear selectivity – the probability that a fish of a certain length or age will be captured by a given gear.

goodness of fit – how well a given model fits the available data; a number of formal statistical approaches are applied to models to examine goodness of fit.

growth overfishing – an action that occurs when mortality rates are outpacing growth rates in terms of the overall weight or biomass of the stock.

growth rate – the rate of growth of a fish stock based on the relationship between net fecundity and mortality.

hindcasting model – see *backward-projecting model.*

incomplete cohorts – those cohorts or age-classes of which some members remain alive in the stock.

index of abundance – numerical value used to demonstrate the trend in relative abundance over time.

index-only model – management approach that attempts to maintain the index of abundance within a certain range, restricting fishing when the index falls below the range and loosening restrictions as the index rises above the range.

instantaneous mortality rate (Z) – the rate at which fish are dying at any given moment. For mathematical purposes, the instantaneous mortality rate is typically converted into an annual rate.

intrinsic growth rate – also called *density-independent growth rate*, a growth rate that does not depend on the abundance, or density, of individuals in the stock. The stock size will change at a constant rate regardless of the size of the stock.

L_{50} – **1.** the length at which a fish has a 50 percent probability of being retained by a gear if it encounters that gear. **2.** the median length of a fish stock at maturity; half of the mature individuals in a population first attain maturity at a length longer than L_{50} and half at a length shorter than L_{50}.

length-age table – key that allows scientists to estimate a fish's age based upon its length.

limit – see *threshold.*

log books – fishermen's records of landings data, also called vessel trip reports. The reports can be valuable for determining the spatial distribution and amount of effort in the fishery.

LVB growth model – also called the *von Bertalanffy growth model*, a model for incorporating growth directly into the stock assessment model by assuming that growth occurs most quickly at the youngest ages, slows gradually as the individual gets older, and eventually levels off. The size at which the individual levels off is referred to as L_∞ ("L-infinity").

Markov Chain Monte Carlo – an approach to estimate uncertainty in a statistical catch-at-age model by beginning with a final model and shifting its associated parameter values slightly to recalculate the model's goodness of fit thousands or millions of times.

maturity ogive – the percentage of mature individuals in each age class.

maximum fishing mortality threshold – see *fishing mortality threshold.*

maximum spawning potential – the biomass of reproductively mature fish per recruit in the absence of fishing.

maximum sustainable yield – the largest average catch that can be continuously taken from a stock under constant environmental conditions.

minimum stock size threshold – see *stock size threshold.*

net fecundity – the number of offspring produced by an individual that survive to recruit into the fishery.

onboard observers – government personnel who sometimes accompany fishing vessels to sample catch for size and age distributions and to estimate bycatch and discards.

optimum yield (OY) **–** the amount of catch that will provide the greatest overall long-term benefit to society. The OY takes into account the biology inherent in maximum sustainable yield, as well as economics and the attitudes of the public towards risk and environmental protection.

otolith – a fish's ear bone, which can be analyzed to estimate the fish's age.

overcompensation – a situation in which the number of recruits starts to decrease when the reproductively mature population is large, due to the mortality rate for recruits increasing faster than the number of recruits being born.

overfished – state of a fish stock that occurs when *stock size* falls below a specific threshold.

overfishing – action that occurs when the *fishing mortality rate* exceeds a specific threshold.

partial recruitment pattern – the pattern of instantaneous fishing mortality rates across all age groups. When older age classes have the highest instantaneous fishing mortality rates, the pattern is known as "flat-topped." When intermediate age classes have the highest rates, the pattern is "dome-shaped."

perfect compensation – a situation in which the number of recruits remains constant as the size of the reproductively mature population increases because the habitat cannot support any more recruits.

plus group – an age class that contains all fish of a certain age and older. Plus groups are often used by modelers to adjust a basic population dynamics model for age structure.

point estimate – a numerical value for parameters such as stock size or fishing mortality rate.

population – a group of individual fish of the same species located in a given area, where the area could be as large as the Atlantic Ocean or as small as a single river.

posterior distribution – also called *posterior predictive distributions*, a series of estimates of the relative probability that a given value is the true value.

priors – explicit definitions about the parameters used in a model employing the Bayesian approach.

proportionality constant – proportional relationship between stock size and index of abundance that remains constant over time.

recruits – offspring that have survived long enough to be counted as part of the stock.

retrospective analysis – analysis that treats the current year as the starting point, then refits the model ignoring this year's data and treating last year as the starting point, then refits the model again ignoring the two most recent years of data and treating three years ago as the starting point, and so on, to look for *retrospective patterns.*

retrospective pattern – a systematic change or pattern in stock sizes or fishing mortality rates that may appear when modelers refit data using various years as starting points.

risk assessment – process that formally incorporates uncertainty into predicting the results of fisheries management actions in order to provide managers with the information necessary to effectively compare various choices.

sensitivity analysis – an analysis that refits the assessment model with different values for the assumed parameters to examine how much, if any, the outputs change.

separability assumption – an assumption that the instantaneous fishing mortality rate for a specific age in a specific year can be separated into two parts – gear selectivity and instantaneous fishing mortality rate for the fully selected age classes – that can be multiplied together to create an age-specific probability that a fish will be caught.

spawning stock biomass – the total weight of the reproductively mature individuals in a stock.

statistical catch-at-age model – a typically forward-projecting model that treats catch as needing to be estimated rather than assumed known without error.

stock – a group of fish of the same species in a given area. Unlike a fish population, a stock is defined as much by management concerns (such as jurisdictional boundaries or harvesting location) as by biology. A fish stock may be only one population or may encompass numerous populations.

stock assessment – an evaluation of the past, present and future status of the stock that includes a range of life history characteristics for a species, such as the geographical boundaries of the population and the stock; information on age, growth, natural mortality, sexual maturity and reproduction, feeding habits and habitat preferences; and the fisheries pressures affecting the species.

stock size threshold ($B_{threshold}$) – also called the *minimum stock size threshold*, the threshold below which a stock is said to be overfished.

targets – levels for fish stocks or mortality rates that managers aim to maintain.

terminal F's – the estimated age-specific instantaneous fishing mortality rates for incomplete cohorts in the most recent year.

thresholds – also called *limits.* Minimum stock size targets, which managers aim to avoid. When a fishery crosses a threshold, actions must be taken to correct the situation.

vessel monitoring systems – electronic devices that automatically record the location of a vessel.

virtual population analyses (VPA) – a type of age-structured population dynamics model, usually backward-projecting, that assumes an exact value is known for the number of fish caught.

von Bertalanffy growth model – see *LVB growth model.*

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