A Guide to Fisheries Stock Assessment using the FMSP Tools

Daniel D. Hoggarth, Christopher C. Mees, Catherine O'Neill,
James Hindson, Mohan Krishna

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Preface

This guide is one of a two-part set written to help fishery managers and those involved in fishery management.

These two guides should be used as a pair to show how managers and scientists (and any co-management partners) need to work together to manage a fishery

- The 'Managers Guide' describes a simple, step by step process for writing and implementing a fishery management plan.
- This 'Stock Assessment Guide' shows how stock assessment tools can support fishery managers in designing their management plans and in managing the fishery. In particular, it refers to stock assessment tools developed under the Fisheries Management Science Programme (FMSP).

The two guides are complementary. The Managers Guide shows where stock assessment is necessary to support the development and implementation of a fishery management plan. This Stock Assessment Guide is designed to help fisheries scientists through the process of undertaking a stock assessment, and in providing the advice that fishery managers require on that topic.

The two guides can be read and used on their own. However, you may also wish to refer to another document – the 'Framework Guide to the use of the FMSP Stock Assessment Tools' – that was produced by a previous FMSP project and published as FAO Fisheries Technical Paper 487 (Hoggarth *et al.*, 2005). That document contains much more details on the process of fishery management and stock assessment, and on the use of the FMSP tools. We refer to it frequently in this document as 'FTP 487'.

This guide focuses on where stock assessment tools are needed in fishery management, which tools may be used in which situation, what advice may be provided to managers, and how to allow for the uncertainty in the assessments. It does not attempt to explain fully the mathematical background of the different tools. This is well covered in the help files included with each software package, and in textbooks such as Hilborn and Walters, 1992; Sparre and Venema, 1998; Quinn and Deriso, 1999; Haddon, 2001; and Cadima, 2003. These publications are referenced at the end of the guide. The guide assumes that you have at least a basic understanding of the principles of fish stock assessment.

This guide assumes that you have some previous experience in fish stock assessment

Outputs from other FMSP projects that may help you to develop your plan are available on the web site

This document was produced by Project R8468 of DFID's Fisheries Management Science Programme (FMSP). The FMSP was established to generate improved livelihood benefits for poor people through the application of new knowledge on fishery management. Since 1992, the FMSP has produced a series of outputs about the assessment and management of fish stocks. These range from new methodologies and software packages for assessing fish stocks and providing advice to fishery managers, to applied research on specific country fisheries. Several of these are covered in this document. For more information on the FMSP and the other projects funded through the Programme, or to download the FMSP software packages, please visit http://www.fmsp.org.uk. Although they have been developed independently and use slightly different conceptual frameworks, you may also find useful complementary material in the latest guidelines for adaptive management produced by FMSP project R8292 (see http://www.adaptivelearning.info/) and the guidelines for data collection produced by project R8462 (see http://www.fmsp.org.uk/).

1 What is the role of stock assessment in fishery management?

Fishery managers develop management plans to state clearly *how* they will manage their fishery (with what management measures), and *why* (towards what goals). Stock assessments provide a scientific and quantitative basis to the process of developing and implementing a management plan in several areas.

A step-by-step process for developing a management plan is given in Table 1 below and described in detail in the complementary Managers Guide. The process we suggest involves four main phases:

I. *Preparing* for planning;
II. *Developing* the plan (setting the goals and objectives);
III. *Developing* the plan (setting the actions); and
IV. *Implementing* the plan and *monitoring* the outcome.

Table 1. Phases and stages in the process of developing and implementing a fishery management plan

Phase		Stage
I. Preparation for developing the management plan **Where are you Now?**	***1***	**Define** Define the fishery your management plan is for
	2	**Stakeholder analysis** Carry out a stakeholder analysis and decide how you are going to involve the stakeholders
	3	**Situation analysis** Carry out a situation analysis and list the problems faced by your fishery
	4	**Management approach** Decide on your management approach
II. Developing the management plan **Where do you want to be?**	***5***	**Purpose** Agree the overall purpose of your plan
	6	**Goals** Decide on the biological, ecological, social and economic goals needed to achieve your purpose
	7	**Objectives** Define objectives for each goal
	8	**Management standards** Agree the management standards – the reference points and indicators for each objective. In other words – what and how you are going to measure to show that you are achieving your objectives

III. Developing the management plan **How are you going to get there?**	*9* *10* *11*	**Management measures** Decide the management measures – in other words,the actions-you are going to take to achieve the objectives **Control rules** Agree a set of decision control rules stating which measures and which levels of measures will be applied depending on the status of the fishery **Resources** Decide what resources you will need to put your plan into action
IV. Planning for implementing, monitoring and reviewing the management plan **How will you know you are there?**	*12* *13* *14*	**Implementation** Make an action plan to implement your management plan **Monitoring** Monitor regularly how well your plan is achieving your objectives **Reviewing** Review your plan every few years

Stock assessment is needed both to help develop a good plan and to ensure that the goals are being achieved

As a stock assessment scientist or advisor, you will need to help with developing and implementing the plan in several of these phases and stages. In the planning phase, you will help managers to make decisions on which management actions are feasible and most likely to enable them to achieve their goals. These types of stock assessment are described below as 'strategic' analyses as they help to decide the management strategy. Further down the line, you will also need to help managers to monitor the outcome of the plan, and ensure that the goals are indeed being achieved. As this advice is often used to fine tune any management measures (e.g. to increase or decrease the quotas, depending on the state of the fishery), these assessments are known as 'tactical' analyses. Brief details on these inputs are given in the following sections.

You will need to meet the fishery manager on a regular basis to develop and implement a management plan

Table 2 below also shows the information that the manager should provide you with at each stage in the process. You will need to meet the Fisheries Manager on a regular basis throughout the process of developing and implementing the management plan to exchange information and ideas.

Table 2. Flows of information between the fishery manager and the stock assessment advisor, at each stage in the process of developing and implementing a fishery management plan

Information that the fishery managers need to provide to fishery scientists	Phase	Stage		Information required by managers from fisheries scientists
Decision on what fishery the plan is for	*I*	*1*	**Define the fishery**	The unit stock for the target fishery based on the of distribution fish stocks and fishing activities. (see Section 1.1)
Stakeholders to be consulted		*2*	**Stakeholder Analysis**	Information on the distribution of the fishers etc engaged in the fishery. (see Section 1.1)
		3	**Situation Analysis**	Historical data on fishin geffort and fish catch etc, showing fishery trends.
Approach to precaution and uncertainty		*4*	**Management Approach**	Pros and cons of alternative approaches to decision making, allowing for uncertainty.
	II	*5*	**Purpose**	
		6	**Goals**	
		7	**Objectives**	
Objectives for each goal		*8*	**Management standards**	Suggest what indicators and reference points could be used as targets or limits to measure progress towards each objective – noting the feasibility and cost implications of any SA involved with each.(see Sections
Which management measures are seen as socially, politically and technically feasible for this fishery	*III*	*9*	**Management measures**	Strategic advice on the expected impact on the indicators of alternative possible management measures, and alternative levels of any control measures. (see Section 1.2, 3, 4, 5.1, 5.3, 5.4)
Approach to uncertainty and degree of risk tolerance		*10*	**Control Rules**	Estimates of uncertainty in the indicators and reference points, and suggested precautionary adjustments to reference points to allow for risk and uncertainty. (see Section 1.2, 5.4, 5.5)
Resources available for monitoring		*11*	**Resources**	What resources are needed for effective stock assessment?

	IV	***12***	**Implement**	
		13	**Monitoring**	Tactical advice updating the estimate of the selected indicators – this is usually done each year – for comparison with the reference points and guiding management actions as agreed in the control rules. (see Sections 1.3, 3, 4, 5.2)
		14	**Reviewing**	Up-dated stock assessment advice allowing for the latest data from the fishery and any changes in the goals and situation.

1.1 Providing advice in the preparatory phase

The plan must relate to a unit stock of fish with clear biological limits

In the first stage of the proposed management planning process – defining the fishery (see Table 2) – stock assessment scientists need to assist managers in identifying the *unit stock* that will be managed. This should be determined with reference to the distributions of both the fish stock(s) and the fishing fleet(s). You need to guide managers to select fishery planning units where there is the best possible overlap between the biological unit (the fish stock or stocks) and the management unit (the fishing fleet or fleets). Take particular care in providing advice on management units for migratory fish stocks (see Sparre and Venema, 1998, Chapter 11).

e.g. Sometimes, a single fish species may be targeted by one or two gears within only your country's waters, providing a natural focus for a management plan. At other times, your fish stock may be shared with a neighbouring country, and a broader collaborative plan will be needed. It may also be practical in some cases to develop a management plan for a multi-species fishery, e.g. the 'demersal' fishery, or the 'shark' fishery, where more than one species is taken by a particular type of gear.

Details of who is fishing the stock with what gear, and whether they are organised into any fishers groups (e.g. a gill net fishers co-operative) will also inform Stage 2, the stakeholder analysis.

In the situation analysis (Stage 3), managers need information on the current state of the fish stocks, the pressures they are under at present, and the threats they are likely to face in future. If detailed stock assessments have not yet been done, you may at least provide what information is available on the trends in fish catches and fishing effort (e.g. numbers of fishing boats, fishers or gears). The ratio – catch per unit effort (CPUE) – can then be used as a rough indicator of the size of the fish stock. Is this stable or declining? Are local human population levels or demand for fish protein increasing? What are the likely implications for the fish stock and the fishery? Social and economic data will also help inform the situation analysis.

The situation analysis should show the trends in fishing patterns and fish catches

Supplementary data collected in the preparatory phase (boat and gear census, socio-economic data, etc) can be updated approximately every five years. If the situation analysis was based only on existing data, and did not include this type of information, it is appropriate to consider implementing a programme of data collection.

1.2 Helping to develop the management plan

In the plan development phase (Phases II and III), you will need to help managers by providing advice in three main areas:

- Options for the management standards (indicators and reference points) that will show whether the fishery is in the state you wish it to be in;
- 'Strategic' guidance on the expected impacts of alternative management measures and controls; and
- Estimates of uncertainty in all the above to assist with designing the management approach and control rules for the fishery.

Detailed stock assessment advice will be particularly important in the plan development stages

Details on these are given below, and more details are given in Chapter 5. This plan development stage is where the stock assessment usually gets most complicated. Thankfully, it only needs to be done every few years – first when the plan is being developed, and again whenever it is being reviewed or updated. Where local capacity is limited, expert assistance for such occasional assessments may be brought in from outside, e.g. by collaborating with your national fisheries research institution, or with the help of consultants.

Suggesting indicators and reference points

As noted in the Managers Guide, managers are responsible for consulting with stakeholders and agreeing the purpose, goals and objectives of the plan. Definitions and advice on setting these are given in the 'Phase II' sections of the Managers Guide. The stock assessment team should help in the selection of objectives by suggesting the *management standards* by which the objectives will be defined and monitored.

To be quantifiable, objectives should be specified in the general form

'verb' – 'indicator' – 'relation' – 'reference point'

(see Managers Guide, Stage 7). The 'verb' in such objective statements might be 'maintain' or 'increase' depending on the current status of the fishery. The 'relation' in the statement might be 'above' or 'below' in the case of a limit reference point, or 'close to' or 'within 20% of' in the case of a target reference point (see Box 2 below about the difference between limit and target reference points). Both indicators and reference points can either be set as arbitrary or agreed_values, or as specific quantities that must be estimated by stock assessment (SA) models.

Objectives are used to quantify the different goals of the fishery, in terms of the indicators and reference points

e.g. You may for example, set an objective to keep the average catch rate (CPUE) of fleet X (the indicator) at or above the average level achieved in 1999 (the reference point). The 1999 catch rate is an arbitrary level, but might have been agreed with industry as a level below which they do not wish to fall. It also has the advantage that no stock assessment is needed to monitor the indicator (apart from the basic estimation of the average catch rate) to see if the objective is being achieved.

e.g. As an alternative, you might suggest trying to ensure that the fishery achieves the 'best possible' results by setting an objective to maintain the total catch in the fishery (the indicator) at the maximum sustainable yield (MSY) level (the reference point). This is perhaps a more rational objective, but it requires rather more investment in stock assessment to estimate the actual size of the MSY yield. You need to explain to managers

Indicators and reference points may be set at arbitrary levels or as quantities that must be estimated by stock assess-ment models these and the various other options for defining management standards, along with the implications for data collection, manpower etc.

'Strategic' advice on the implications of alternative management options

In the next stage, managers need to decide which *management measures* they will use to attempt to achieve their goals and objectives. Managers should discuss with the fishery users which measures are socially, politically and/or technically feasible for the fishery. In some places, for example, restricting access to the fishery may be considered impossible either because of the social implications or the technical difficulty of enforcement. A short closed season, or a gear ban may however be more acceptable.

Strategic stock assessments give advice on the implications of alternative management options for each of the fishery goals

Having been told which measures to consider, you need to undertake 'strategic' stock assessments to advise managers on which of them might work best. Would that closed season or other technical measure actually achieve your objectives, for example? This should be judged according to the_expected performance_of this and other options against each of the different objectives – biological, ecological, social and economic. No management option will ever simultaneously maximize all the potential benefits and minimise all the potential risks. You therefore need to provide advice on the expected implications of alternative management options for each management objective (measured as the expected values of the indicators, relative to the reference points).

Strategic SAs, then, predict what may happen in the fishery under a number of different management approaches (alternative 'scenarios') that managers may consider for managing the stock. Depending on the management measures considered feasible for the fishery, example scenarios could estimate the effect on the fishery objectives of:

e.g.

- a reduction in catches of 10%, 20%, X%...e.g. by enforcing a catch quota;
- the closure of 10%, 20%, X%... of the fishing grounds to fishing;
- the introduction of a mesh size limit of 18cm, 20cm, Xcm…; or
- a complete ban on all fishing (how long would the stock take to recover?).

As noted in Chapter 5 below, such strategic assessments should take careful account of the uncertainties in the system. They may also consider the time frame over which the reported impacts would occur. Strategic assessments may also help in guiding the selection of reference points and the actual formulation of the control rule system, as described next.

Estimating uncertainty and helping to design the fishery control rules

You need to tell managers clearly about the uncertainty in your assessments and ensure that they are balanced by the precaution in the management plan

One of the most important parts of the management plan is the 'decision control rule framework' (see Managers Guide, Phase III). This is a set of rules, which should be agreed with stakeholders in advance, that guides decisions on the management of a fishery (i.e., what actions will be taken if the fishery is *not* in the desired state).

e.g. A control rule may state, for example that a closed season (one of the management measures) should be increased in duration by one month, if the proportion of immature fish in the catch (one of the fishery indicators) rises above the arbitrary level of 20% (the reference point). If fishermen are aware this will occur, they might be less inclined to adopt small meshed gears that would catch more immature fish.

Strategic stock assessments help with setting control rules by showing which management actions would be most likely to achieve the desired objective. In the example above, would the extra month's closed season reduce the capture of immature fish, or would this be better achieved by a mesh size limit, or a gear ban?

You can also help managers to set control rules by estimating the uncertainty in your assessments. Managers need to be aware of how much confidence you have in your predictions. Usually it is not very much, especially where data are limited in quality or quantity. With this information, managers can set control rules with 'precautionary adjustments' so that action is taken a bit earlier than you recommend, in order to be on the safer side. Just how much early it is necessary depends on the uncertainty that you report, and on how much risk the manager is prepared to accept.

1.3 Fine tuning the management measures in the implementation phase

Tactical stock assessments are used to monitor the state of the fishery in the implementation phase and to guide management actions

In the implementation phase (Phase IV), the management goals, objectives, standards, measures and control rules should all have been decided and agreed with stakeholders. Your job is then to keep monitoring the selected indicators to be sure they are on the safe side of the selected reference points. If they are not, you should provide 'tactical' stock assessment advice on what to do about it (as guided by the decision control rules).

In this phase, you should be providing tactical advice on an agreed regular cycle, e.g. annually. Exactly what is required will depend on what has been agreed earlier in defining the management system.

The management plan should also be reviewed every few years by repeating the strategic stock assessments. This may lead to the control rules, reference points, or other elements in the management plan being modified, if they are found to be inappropriate or failing to achieve the agreed objectives.

In summary then, you should be providing two main types of stock assessment advice:

- Strategic (long term) advice, initially on what management measures might best achieve the objectives, and later on, whether a change in the overall management strategy might give better returns; and
- Tactical (short term) advice on whether a change in the management measures is needed next year and if so, how much.

A good stock assessment should present a range of choices and show the benefits and risks of each

While stock assessments may form the primary basis for choosing management strategies, they should not be expected to do the impossible – predict the future with certainty. A good stock assessment, therefore, will not provide a single right ‘answer’, but should rather give a range of choices showing the predicted outcomes and any trade-offs. The choice between such options should be made by fishery managers, guided by their attitudes towards risk and the socio-economic priorities for the fishery, and not by stock assessment scientists.

2 What is a stock assessment?

2.1 What will I estimate in a stock assessment?

Your stock assessments will produce two main types of information for use by managers:

- 'Reference Points' for the fishery, showing where you would like to be; and
- 'Indicators', showing where the fishery is at the moment, or predicting where it might be in future if different management measures are applied.

Indicators show the state of the fishery; reference points are particular values of indicators and show the states you would like to achieve or avoid

Indicators and reference points are used in combination to clearly define the objectives in ways that can be estimated in *quantitative* fishery assessments. Whether you will estimate reference points, indicators, or both in a stock assessment depends on what stage you are at in the planning process, as described above. Further details on the different types of stock assessment are given in the following chapters and annexes.

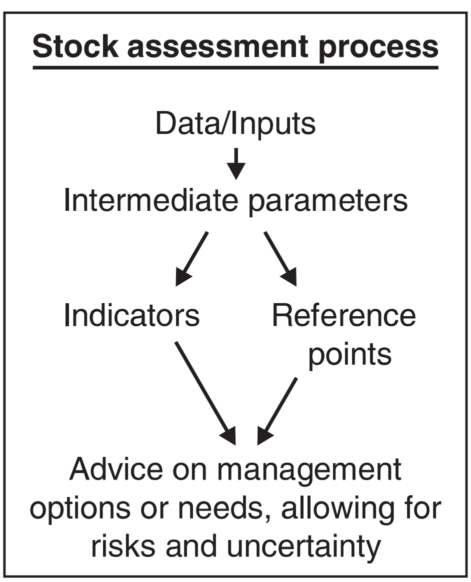


Figure 1. Key elements of a stock assessment (see contribution of this box to the overall management process in Figure 1.1 in the companion 'FTP 487' document)

You can use different SA tools to estimate different reference points and indicators. These tools often work in quite different ways and use different data. Two general categories of stock assessments are the 'analytical' and 'biomass dynamic' approaches. These are described in Section 2.2.

Stock assessments are always based on quantitative data collected from the fishery. The types of data that may be needed are listed in Section 2.3. As shown in Figure 1, stock assessments also often involve the estimation of 'intermediate parameters', (such as, growth rates or the size at maturity) before getting to the main points of interest - the indicators and/or reference points. The following sub-sections briefly describe the different types of indicators and reference points that you might estimate.

Indicators

Your manager needs 'indicators' to monitor the current status of the fishery and see if the fishery objectives are being achieved. Each objective should be represented in quantitative terms by a particular indicator.Fishery indicators derived from typical stock assessments often fall into one of the three categories:

- The catch of fish;
- The size of the fish stock (often expressed as the 'biomass'); and
- The amount of fishing.

Depending on your objectives, you may also need to monitor various social and economic indicators. Whatever else is required, these three essentially biological indicators jointly define the status and potential productivity of the fishery as described below. In the short term, these three categories of indicators are directly related to each other by the approximate expression:

$$\text{Catch} = \text{Fishing rate} \times \text{Biomass}$$

For a given fishing rate, a larger biomass will naturally produce a larger catch. Equally, for a given biomass, a larger fishing rate will also produce a larger catch.

To be sustainable, however, we need to make sure that we leave enough stock each year to maintain high levels of spawning and replace those fish that are caught. If we fish too hard or allow the stock to become too small, the potential catch will be reduced. In the long term, then, the 'equilibrium' relationships between these three indicators are as shown in Figure 2. The maximum potential catches will generally be taken by reducing the stock size from its unexploited level, and by fishing at a moderate rate, not too high. The long-term catch should be higher at an intermediate stock size than at the unexploited level because there should be more food available to each fish, so they compete less with each other and grow faster.

You can use biomass indicators to show whether the fish stock is currently 'overfished', compared to any selected reference points. In the top left graph of Figure 2 for example, the stock size (represented by the circle symbol) is well below that intermediate biomass that would give the maximum sustainable yield or 'MSY', indicated by the highest point of the catch curve. Similarly, if a good time series of data is available,_your fishing effort indicators can show whether the fishery is currently 'overfishing' the stock, and thus whether it is likely to become even more overfished in future.

Catch, effort and stock size indicators show the position of the fishery relative to the MSY point – too much fishing will reduce both stock size and catches to zero

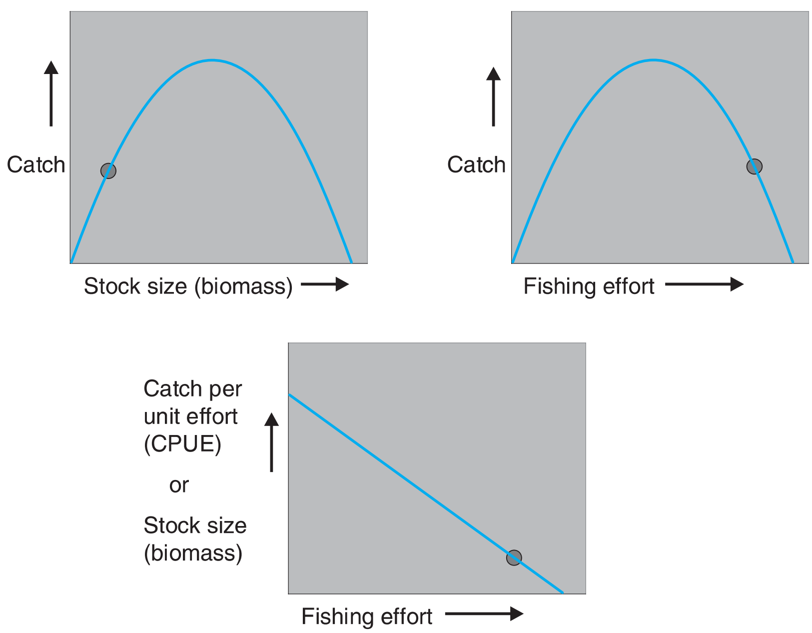


Figure 2. The long term relationships between the key fishery indicators, catch, stock size (biomass), and fishing effort (or fishing mortality rate)

The low catch at a low stock size in the top left graph corresponds to the low catch at a high fishing effort in the top right graph. The circle symbols thus indicate the equivalent positions of a heavily exploited fishery with a low current stock size and CPUE, producing less than its maximum potential catch or MSY.

Due to the time taken for fish stocks to respond to fishing pressures and the natural variation in recruitment and stock sizes, it is quite possible for the stock to be overfished even if overfishing is not presently occurring, and vice versa. In these cases, you need to think carefully about what actions to take (e.g. using projections – see Section 5.3). You are definitely in trouble if your analyses suggest that your fish stock is overfished *and* your fleet is still overfishing (see Section 5.2).

As fishing effort increases, CPUE and stock size will both decrease

The bottom graph in Figure 2 shows that the stock size is inversely related to the long-term average fishing effort. The more you fish, the lower the stock size will become. As shown in the graph, the catch per unit effort or CPUE is often assumed to be proportional to the stock size (so the y-axis can represent either biomass or CPUE). This is important, as managers will need to find a balance between allowing as much fishing as possible (i.e., by increasing effort) and maintaining over the long-term a reasonable CPUE for each fisherman or fishing vessel (i.e. by reducing effort). This is a trade-off in objectives that many managers will need to resolve.

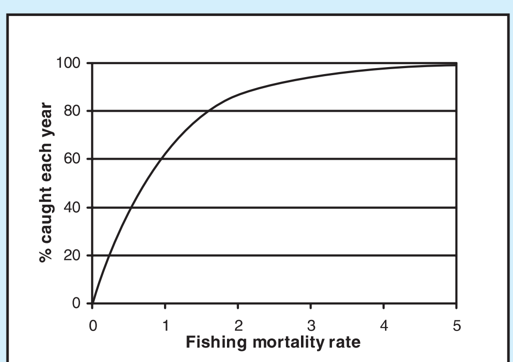
The fishing mortality rate, F is a measure of the amount of fishing pressure on the stock

A commonly used indicator of the amount of fishing is the 'fishing mortality rate', *F* (see Box 1). This is commonly assumed to be directly proportional to the amount of fishing effort being used and the fishing pressure that is being placed on the stock. Several reference points are based on this indicator.

Box 1. What is this 'fishing mortality rate'?

The fishing mortality rate, *F*, is the 'instantaneous exponential rate' at which fish are removed from the fish population by fishing. If there were no deaths due to natural causes, the number, *N*, remaining in a population at time *t* could be estimated as $N_t = N_0 e^{-Ft}$. Rearranging this equation and taking natural logs gives $\log_e(N_t / N_0) = -Ft$. If you get your calculator out, you will see that an *F* of 1 per year implies that 63% of the population will be caught each year. *F*'s of 2 and 3 per year imply that 86% and 95% of the population are being caught each year, respectively. Even if the fishing mortality rate becomes very high, the maximum catch that can be taken is of course only 100% of the fish stock (see figure), and that can only be taken once.

Some fish also die of natural causes of course. This is said to occur at a 'natural mortality rate', *M*. With both fishing and natural mortality, the number remaining in the population at time *t* is estimated as $N_t = N_0 e^{-(F+M)t}$. *F* and *M* together make up the total mortality rate *Z*. Methods for estimating *F* usually involve estimating *Z* and then getting *F* by subtracting *M* (see FTP 487, Sections 3.3.3 and 3.4.3).



Reference points

For each objective selected by the managers, you need to suggest a 'technical reference point' stating exactly how it could be estimated or measured. These reference points are particular values of the indicators that may either be used as targets (points to aim for) or limits (points to keep away from) (see Box 2). Once they are agreed in principle, you may use SA tools to estimate their values in your fishery (see Chapter 3).

Box 2. Using reference points as targets and limits in managing the fishery

In your stock assessments, you will be estimating actual values of technical reference points, for comparison with the indicators. For example, you might estimate the reference point F_{MSY} so that it can be compared with the current fishing mortality rate F – the indicator of fishing pressure in the fishery.

As described in the Managers Guide (and FTP 487), managers use these reference points to guide when to take pre-agreed management actions within decision control frameworks. Reference points may either be used as 'targets' or 'limits'. These provide signposts for the manager: "here you are doing well" (target), or "go any further down this route and we are in trouble" (limit). If your F_{MSY} technical reference point is used by the manager as a limit reference point in the decision control rule framework, this means that the fishing mortality rate must not be *more than* that level. If you use the corresponding biomass B_{MSY} as a limit, then the stock should not be any *less than* that amount. The 'relation' term in the definition of the objective will also imply whether the reference point should be used as a limit or a target (the relation terms 'above' and 'below' both imply limit reference points).

Recognising the uncertainty in the stock assessment process, decision control rules may also include 'precautionary' reference points: these provide thresholds at which initial actions can be taken to reduce the risk that the limits may be broken.

Fishery performance is measured by comparing the indicator to the reference point

Your manager will measure the 'performance' of the fishery as the relation between the indicator and the reference point, comparing the present position with the desired one. As shown in the summary Table 3 below, a 'performance indicator' is thus an indicator that is expressed as a ratio (or percentage) of its associated reference point.

Table 3. Purpose and examples of indicators and reference points estimated in stock assessments or used to guide fishery management actions. (For further details, see FTP 487, Sections 2.5.4, 3.4 and 3.5)

	Purpose	Categories and examples
Indicators	Measure the current position of the fishery for each objective	• State, e.g. stock biomass, B_{now}; total catch • Pressure, e.g. fishing effort; fishing mortality, F_{now} • Response, e.g. quota allowed; size limit set; % of total area set aside as MPAs
Technical reference points	Explicit mathematical definitions and/or procedures for use as targets or limits in decision control rules	• MSY-based, e.g. B_{MSY}, F_{MSY}, as proposed by the UN Convention on the Law of the Sea, now usually recommended as limit reference points, not targets; • Proxies[1] for MSY, e.g. $F_{0.1}$, F_{max}; • Protection of reproductive capacity, e.g. $F_{\%SPR}$, also often used as limit reference points; • Risk-defined, e.g. $F_{transient}$ in 'Yield' software; • Multispecies, e.g. permitted bycatch levels; • Economic and social, e.g. F_{MEY}
Performance Indicators	Measure the current state of the fishery, relative to the associated reference points	• B_{now} / B_{MSY} • F_{now} / F_{MSY}

1 Proxy reference points are used when the preferred reference points can not be calculated, e.g. due to unavailable data.

Though the estimation methods may differ substantially, most reference points focus either on the yield that will be produced or the level of protection that will be given to the spawning stock and its recruitment potential. Yield-based reference points are most often used as targets for management. Reference points for maintaining the reproductive capacity of the stock are more often used as limits to ensure the conservation of the stock.

e.g. Familiar examples of technical reference points based on defined population dynamics models include:

- B_{MSY} Stock size (*B*) giving the maximum sustainable yield (MSY) in a production model (i.e. the highest point in the curve in the top left graph in Figure 2);
- $F_{20\%SPR}$ *F* giving a spawning stock biomass per recruit (SPR) of 20% of the un-fished level.

The pros and cons of these and other reference points are summarised in Table 4. Although the reference points often focus on particular values of the catch or stock size indicators, you will notice that many of them also refer to the fishing mortality rate that will achieve these states. Particular fishing mortality rates can be achieved by management adjustments in catch or effort control measures.

Particular fishing mortality rates can best be achieved by adjustments in catch or effort controls

As noted earlier in Section 1.2, you should also keep in mind the option of setting reference points at 'common sense' or arbitrary values. These might not be explicitly based on technical models but could nevertheless be agreed with the stakeholders.

Table 4. Summary comments on some technical reference points that may be estimated using the FMSP tools (see also Section 3.5 in FTP 487 for others)

Technical reference points	FMSP Tool	Advantages / application	Disadvantages / comments
MSY, f_{MSY}, B_{MSY}, F_{MSY}	CEDA / ParFish Yield	• Yield-based reference points mentioned in UNCLOS, UN Fish Stocks Agreement etc, recommended for use as limit reference points • Estimate using biomass dynamic or analytical models with SRRs • Estimate directly from SRR for semelparous (annual) fish species	• Biomass dynamic models only give precise values of F_{MSY} and B_{MSY} if q is well known • Note that MSY is not a constant but will vary according to environmental and food web conditions. A long term average MSY may exist but may be hard to estimate and may vary with 'regime shifts'.
F_{max}, $F_{0.1}$, $F_{0.x}$	Yield	• Yield per recruit (YPR) reference points used as 'proxies' for F_{MSY} where SR data not available • Used to avoid growth overfishing	• No consideration of spawning capacity, so need to use as target reference points along with, e.g. $F_{\%SPR}$ as a limit reference point.
F_{crash} / F_t	CEDA / ParFish Yield	• Most extreme reference point indicating fishing level associated with stock collapse • Estimate using biomass dynamic or analytical models with SRRs	• Requires SR data to fit· • Need to use with strong adjustment to allow for precaution

$F_{\%SPR}$	Yield	• Spawning capacity reference point from per-recruit models including reproduction data (e.g. maturity, fecundity). • Does not require SRR data to estimate	• Optimum level of %SPR uncertain - values of 20-30% suggested by previous studies, depending on species characteristics
Size-based	—	• Use to protect spawning potential by ensuring that at least some fish have the chance to spawn before capture • May be useful where fish can not be aged or fisheries are small-scale or less valuable	• Approximate • Optimum size limit may need to be adjusted depending on the fishing rate
Risk based,e.g. $F_{transient}$	Yield	• Set *F* for explicitly defined risks using multiple simulations • Note that each of the other reference points in this table could also be estimated with uncertainties, and used in precautionary decision control rule frameworks (see examples below)	• Need information on uncertainty • Need managers to define acceptable risk levels
Multi-species	MS guide-lines	• Define permitted bycatch or discarding levels etc • Set *F* to protect most vulnerable species	• May be hard to optimize and need clearly agreed goals and prioritisation • May underutilise some species

Different reference points involve different assumptions and can refer to very different positions on the catch-effort-biomass curves; you need to carefully consider which one/s to use in your fishery

And what about those 'intermediate' parameters?

We mentioned earlier that most stock assessments involve some initial fitting of intermediate parameters that are then used in some final model (or models) to estimate the indicators and/or reference points needed by managers (see Box 3). These intermediate parameters are a necessary part of each approach and can be time-consuming and difficult to estimate. It is important to keep in mind though, that they are only steps in the process and not directly of interest to managers. Different stock assessment tools may sometimes be required to estimate the intermediate parameters and the indicators and reference points (see e.g. the use of LFDA and Yield in the analytical approach in Annex 3).

You can not advise your managers on what to do with the fishery if you only estimate the intermediate parameters

Box 3. Types of intermediate parameters used in SA models

Intermediate parameters can include both biological parameters (e.g. growth and maturity) and those related to fishing (e.g. catchability and selectivity).

Key intermediate information for the analytical fishery models include the growth rates of individual fish, the natural mortality rate, *M*, the reproductive biology and the exploitation patterns. The relationship between the stock size and the numbers of new fish that are spawned and recruit to the fishery (the 'stock-recruitment relationship') is difficult to fit but very valuable for setting reference points that protect the spawning potential of the stock.

Key intermediate parameters for the biomass dynamic models are the intrinsic rate of population growth, *r*, and the carrying capacity, *K*, of the fish stock.

Both models can also require an estimate of the catchability coefficient, *q*, if (relative) fishing mortality rates (*F*) are to be converted to (absolute) fishing effort levels (*f*) for use in setting management measures (by the relation $F = q\ f$). Common uses and fitting methods for these and other intermediate parameters are given in the companion FTP 487 document.

2.2 Are there alternative approaches to stock assessment?

The 'analytical' and 'biomass dynamic' stock assessment approaches make different assumptions about the fishery, use different data and estimate different reference points

There are actually many different approaches to making a stock assessment. Two common approaches which you could try out with the FMSP tools involve the use of 'analytical' and 'biomass dynamic' models.

Both of these approaches model the relationship between fishery inputs (fishing) and outputs (catches). In the 'analytical' approach (also called the 'dynamic pool' approach), a number of intermediate processes are also modelled that describe in detail the dynamics of the fish stock and the fishery. Such intermediate processes can include the growth and maturation of the fish, and the selectivities of the fishing gears towards different sizes of fish.

In contrast, 'biomass dynamic' models are more direct 'in-out' approaches in which the productivity of the resource is represented only by the size of the stock and its overall rate of turnover. These models estimate the maximum sustainable yield or 'MSY' available from a stock with that size and productivity. Individual processes such as fish growth and gear selectivity are ignored, and models are fitted with a time series of catch, effort and/or abundance data either from the fishery or from surveys (see Box 4).

Box 4. How do the biomass dynamic models estimate MSY?

If the abundance of the fish stock has declined over a certain period of time, it may be assumed that the catches in those years were in excess of the natural rate of production and were thus 'mining' the stock unsustainably. If lower catches in other years allowed the stock abundance to increase over time, those catches may be assumed to have been sustainable. Somewhere in between these two catch levels is the 'MSY' for the fishery. Biomass dynamic models use time series of data to estimate the relationships between the potential catch, fishing effort and biomass from the trends in the fishery. For further details on this approach, see the illustration of using CEDA to fit a biomass dynamics model in Annex 4.

So biomass dynamic models are simpler, but are they still reliable?

For many years, fishery scientists considered age-structured analytical models superior to biomass dynamic models. This was partly because the original methods for fitting biomass dynamic models assumed that the input data came from a stock in an 'equilibrium' state. Those methods tended to overestimate the potential catches available from the fishery because they failed to take into account the declines in the fish stocks during the time series. The more recent non-equilibrium, dynamic fitting methods used in tools such as CEDA, however, can produce reliable outputs at least where the data have good contrast. They can also show you when your data are insufficient or incompatible with the method, by failing to find any sensible solution. This is still better than providing 'bad' advice. Biomass dynamic models work best where the data set includes periods of both high and low catches, preferably at different stock sizes. Many data sets unfortunately are too short or have little 'contrast'. In these cases, only one side of the picture may be known (either that catches are 'sustainable' or 'not sustainable'), and the MSY may remain unclear. This reinforces the need for fisheries agencies to ensure that they collect good catch and effort data on an on-going basis.

Neither approach is more right or wrong than the other – try both if you can

Both biomass dynamic and analytical approaches may produce useful guidance for managers. If you have the data, you should try out both approaches, and compare the results. Neither approach is more right or wrong than the other – they are just based on different models and assumptions, and use different data (see Box 5).

As described in the next chapter, both analytical and biomass dynamic models may be fitted using the FMSP software tools. You could use

LFDA and Yield, for example, in an analytical stock assessment approach (see Annex 3) or the CEDA software to run a biomass dynamic model (see Annex 4). These general approaches and others are described in standard fishery text books such as, Gulland, (1983); Hilborn and Walters, (1992); and Sparre and Venema, (1998). Some stock assessment approaches used in very 'data-rich' fisheries are actually a combination of these two basic model forms.

Box 5. What are the pros and cons of the two approaches?

Analytical models require a reasonable understanding of the population dynamics of the stock. Although several input parameters need to be estimated, most of these can be estimated by a short but intensive period of data collection (e.g. for fish length frequencies and biological data). With these models, you will be able to provide advice on a range of different management measures including catch and effort controls and technical measures (mesh sizes, closed seasons, etc).

Biomass dynamic models need less detailed data (only catch and effort) but they need a long time series to give good results. They can be particularly useful for fish species that are hard to age, or for multi-species resources where single-species analytical models are impractical, e.g. where resources are not available to collect data on each of the different species, or for enforcement of species-specific regulations. Since they ignore the size structure of the fish, however, they can not give advice on technical management measures such as mesh size limits or fish size limits, or fishing seasons. They are usually used instead to provide guidance on total allowable catch quotas and/or fishing effort limits (e.g. limits on the numbers of fishing vessels).

Further guidance on selecting these or other models is given in Chapter 4.

2.3 What data would I need?

Exactly what data you need will vary according to the objectives selected for the fishery, the SA tools you propose to use, and the indicators and references points you wish to estimate. For the two stock assessment approaches above, you would need at least these data:

Data needs will depend on the_objectives of the fishery and the stock assessment approach that is adopted

For the biomass dynamic approach (see Box 6)	For the analytical approach (see Box 7)
Multi-year time series of catch and effort data, or catch and some other index of abundance	• Catch composition data (e.g. from length frequencies or ageing studies) • Biological data (e.g. size at maturity)

The best ways of collecting data will vary between fisheries, depending on the budgets available, the landing and marketing routes of the catches, the extent of cooperation with industry, and various other factors.

Multi-year time series of catch and effort data are needed for biomass dynamic models

Catch and effort data are usually obtained by interviewing fishers as they land their catches at port, or by the submission of log books. Port landings are usually sub-sampled and raised to total catches within different 'strata' based on a 'frame survey' of the numbers of active vessels. As described in Box 6, catch and effort data may be used directly in biomass dynamic models because, under certain conditions, CPUE gives an index of abundance. A good time series of catch and effort data can allow you to estimate the catchability, *q* and, from that, the time series of abundances. Better results may be obtained, in some cases, if you use a survey based estimate of biomass or abundance.

Box 6. Using catch and effort data or surveys as an index of abundance in the biomass dynamic approach

Long term trends in total fish catches show broadly whether the fishery is developing, mature or in decline (see FTP 487, Chapter 14). In combination with effort data, *catch per unit effort* (CPUE) is used as an index of the abundance of the fish stock. This is one of the most important indicators for the fishery, and a key data requirement of the biomass dynamic approach. Abundance indices may either be estimated from the CPUE in the commercial fishery, or using various types of 'fishery-independent' surveys. Commercial fishing tends to concentrate on the main densities of the stock, and may therefore not reflect the overall situation of the whole population. Fishing vessels and technology also change over time and fishers become more knowledgeable about the best fishing strategies (times, places, methods, etc). The catching power or 'catchability' of the commercial vessels thus tends to increase with time, and CPUEs from the fishery rarely provide a very good index of abundance. Survey-based abundance indices are less biased for spatial effects and effort changes because the survey track and the fishing gear used can be kept constant over the years. Samples from commercial fisheries may however, be cheaper and easier to obtain in large quantities than research vessel survey data.

For the analytical approach, you can estimate the catch composition either by age or length. To estimate the age composition, you would need to age a sample of fish from bony parts such as otoliths or scales. Rings formed on these parts each year show the age of the fish, just like a cross section through a tree trunk. Since some fish (and particularly crustaceans) are hard to age like this, length frequency samples can be taken instead and fish growth estimated from the progression in the mean lengths of fish with time (see Annex 3). Where ages can be estimated directly, this will usually give more reliable estimates of mortality rate indicators than any of the length based methods.

Size or age composition data are needed for the analytical models, but only a one-year time series may be needed

For valuable fish stocks, you should ideally collect both catch/effort (or abundance) data and catch composition data every year. With a good sampling programme, these will enable you to estimate stock size and fishing effort indicators, and a range of different reference points.

We recommend you collect both types of data and assess the fishery using a range of different models

Box 7. Using catch composition and other data in the analytical approach

In addition to reducing the overall abundance of fish, fishing changes the age and size composition of the stock. With more fishing, there will usually be relatively fewer older fish and fewer large fish. The analytical models thus use catch composition data to estimate the relative abundance of different age classes or cohorts. This information is then used to determine the current fishing mortality rate in the stock, F_{now} from the relative numbers of old and young fish. Catch composition data also reveal the selectivity of the fishing gears and can be used to estimate the growth rates needed in analytical models.

Other biological data needed for the analytical approach include the sizes (or ages) at maturity, the fecundity (the number of eggs produced at a given size), and the average weight at length (or 'condition factor'). Information on spawning seasons and feeding patterns may also be useful to understand the seasonality of growth and recruitment and to consider the possible value of closed seasons in managing the fishery. Special sampling programmes are usually used to estimate these characteristics, perhaps every few years.

A further option to consider is the FMSP ParFish tool (see Annex 5). This is based on a biomass dynamic model, and can use catch/effort data like CEDA. Where no historical data are available, you can still use ParFish to make an initial stock assessment based on interviews with local fishermen. This uses their knowledge of the fishery's potential which may be quite good for small scale, inshore resources.

3 What tools can I use to make a stock assessment?

This guidebook focuses particularly on four software tools developed by the FMSP:

- Length Frequency Distribution Analysis (LFDA) . . . . see Box 8
- Yield . . . . see Box 9
- Catch Effort Data Analysis (CEDA) . . . . see Box 10
- Participatory Fisheries Stock Assessment (ParFish) . . . . . . see Box 11

You can download these software tools for free from the FMSP web site

These FMSP tools are described in the boxes listed above and in much more detail in FTP 487. The annexes to this guidebook provide a short overview of the use of each tool, showing how they work and what advice you could provide to managers in each type of assessment. Further guidance is also available in the help files and tutorials provided with each software package. The software packages were distributed on a CD with FTP 487, but may also be downloaded for free from the FMSP website: http://www.fmsp.org.uk.

Other FMSP tools are described in the complementary FAO Fisheries Technical Paper (FTP) 487

The FMSP has also produced a range of other guidelines and methods for making stock assessments. Some of these are described in Part 3 of FTP 487. Chapter 11 of that guidebook, for example, gives a method based on the 'Beverton and Holt invariants' which can estimate the reference point F_{max} with only minimal data, assuming standard 'invariant' dynamics in your fish stock. Chapter 14 gives equations for estimating the potential average catches in river, lake, coastal lagoon and coral reef fisheries, according to their areas, and suggests methods for 'empirical' analysis of complex fishery systems. And chapter 12 provides guidelines for analysing multi-species fisheries; these are summarised in Section 3.3 below.

You should also be aware that there are many other tools that you can use for providing management advice, including the FAO FiSAT suite, and Lassen and Medley's, (2001) VPA, spreadsheets. You can also develop your own spreadsheets, either from scratch, or by building on existing templates such as those given by Haddon, (2001) or Punt and Hilborn, (2001).

The following sections make brief comparisons of the advice available from each tool, and the types of stock assessment they can be used in. The data needed by each tool is described in the four boxes (and see also Section 2.3, and Tables 5.1 and 5.2 in FTP 487).

3.1 What do the different FMSP stock assessment tools estimate?

The outputs produced by the different FMSP stock assessment tools are shown in Table 5.

LFDA estimates growth and mortality rates; Yield estimates reference points

The LFDA package estimates the growth rates as intermediate parameters, and then uses them to estimate the total mortality rate. By subtracting the natural mortality rate, you can then get a rough estimate of the 'equilibrium' fishing mortality rate – the key indicator of the level of fishing pressure. The Yield software uses the growth rates from LFDA and other biological intermediate parameters to estimate a range of indicators and reference points. These two packages can be used together in the 'analytical' approach to stock assessment, as described in Section 2.2 and Annex 3.

CEDA fits biomass dynamic and other models using C/E data

The CEDA package can be used on its own to fit biomass dynamic models, and thereby estimate the current size of the fish stock, and the 'MSY' based reference points. This approach requires a long time series of catch and effort or abundance data (see Section 2.2 again and Annex 3). The 'depletion' model in CEDA can also be used with a shorter set of catch/effort data, perhaps taken over just one season, or as repeated hauls through a lake or pond, to estimate the stock size at the start of fishing.

ParFish is a new approach aimed at co-managed fisheries

The ParFish software can also be used to fit the 'Schaefer' biomass dynamic model used in CEDA. With its 'Bayesian' formulation, ParFish can also use other data to improve the analysis. As described in Annex 5, this can be particularly useful where little or no existing catch/effort data are available, and also in a co-management situation.

Table 5. Stock assessment parameters estimated by the different FMSP tools (see Table 4 for further information on the different reference points)

Type	Parameters		LFDA	Yield	CEDA	ParFish	Empirical methods	Beverton and Holt invariants
Intermediate	r, K, q	(production model)			●	●		
	K, L_∞, t_0	(von Bertalanffy growth)	●					
	M	(natural mortality rate [1])		●			●	
	Z	(total mortality rate)	●					
Indicators	YPR / BPR	(yield/biomass per recruit)		●				
	Yield / biomass	(absolute,equilibrium[3])		●				
	B_t	(biomass in year t)		● [2]	●	●		
	N_t	(numbers in year t)		● [2]	●			
	F_{eq}	(fishing mortality rate, Z-M)	●					
	CPUA	(catch per unit area)					●	
Reference points	MSY, f_{MSY}, B_{MSY}, F_{MSY}		●	●		●	● [4]	
	F_{max}, $F_{0.1}$, $F_{0.x}$, $F_{\%SPR}$	(per recruit)		●				
	F_{MSY}, $F_{\%SSB}$, F_{crash}	(absolute [3])		●				
	$F_{transient}$	(risk-based)		●				
	f_{lim}, C_{lim}	(risk-based, biological limits)				●		
	f_{opt}, C_{opt}	(adjusted for 'preferences')				●		
	F_{max}	(max yield per recruit)						●
	F_{MSY}	(max absolute yield [3])						●

Available FMSP tools: LFDA, Yield, CEDA, ParFish, Empirical methods, Beverton and Holt invariants.

1 *Using Pauly equation.*

2 *Yield will project future trajectories of biomass and numbers based on current estimates of those values, but will not provide the current estimates. These need to be derived by other means and fed into Yield.*

3 *'Absolute' yield and biomass reference points require data on the stock-recruit relationship to estimate (as compared to 'per recruit' points which do not).*

4 *On a per unit area basis, by comparison with catches in other similar fisheries, assumed to be operating at MSY levels.*

Note: The letter 'K' is used for two different parameters in the production model and the von Bertalanffy growth model.

3.2 So which types of stock assessments can I use the different tools for?

Which tools can I use to evaluate different management measures in strategic stock assessments?

All of the tools can be used to manage the fishery using catch and/or effort controls

As shown in Table 6 below, you can use any of the different tools to provide advice on setting fishing effort levels and catch quotas, also known as the ‘input’ and ‘output’ controls (see FTP 487, section 2.5.5). With the biomass dynamic approach used in CEDA and ParFish, the model directly estimates the MSY catch and the effort level, f_{MSY} that would produce it. With the analytical approach used in Yield and the Beverton and Holt invariant method, you estimate *F*-based reference points and therefore also need to have some estimate of the current *F* for comparison, e.g. from LFDA. You can use these to give advice on effort levels by suggesting adjustments based on the ratio of the indicator and the reference point. To give advice on catch levels with these tools, you would need to know the current biomass and make a short-term projection using your selected *F*-based reference point.

You could compare the relative costs and benefits of these input/output controls with alternative ‘technical measures’ using Yield or ParFish. As shown in the table, Yield allows you to investigate the likely effect on your indicators of different closed seasons or of using minimum size limits. With ParFish you can compare the effect of using a closed area, at least in a simple way, assuming that fish will not migrate out of the refuge, but will produce more new recruits for capture in the fishery.

You can set ‘common sense’ technical measures using only biological studies, but you may still need some stock assessments and catch or effort controls to avoid overfishing

Table 6 also emphasises that you could set basic technical regulations – closed seasons, size limits, etc – based on relatively simple biological studies. You could, for example, set a mesh size limit to ensure that fish are not caught until they are larger than the size at maturity, to ensure that most fish can spawn before capture. You could also use a closed season to prevent too many small fish being caught, or to protect adults while they are on the breeding grounds. Many fisheries are managed with these types of measures, and they may be enough on their own in some cases, provided that they have been properly set and demonstrated to be sufficient to achieve the biological objectives. For example, if a minimum size is used as the primary management measure, it must be set high enough, and properly enforced, to ensure that the spawning biomass will be sufficient to maintain adequate recruitment, no matter how high the fishing pressure on the legal sized animals. Similarly, a closed season would need to be of sufficient duration to ensure that the spawner biomass remains above the limit reference point no matter how high the fishing pressure during the open season. In practice, this may require very short open seasons where fishing capacity is high. It has generally been found that technical measures are rarely sufficient on their own and need to be supplemented with rigorous control of fishing capacity and effort.

If you have technical measures in place and the fishery still seems to be declining, or if you can't use them in your fishery for some reason (e.g. if the juvenile fish are the main marketable product), you need to start thinking about those input/output controls too. Controlling the overall amount of fishing will thus be necessary in many fisheries to avoid 'recruitment overfishing' (see Box 24) and the risk of stock collapse. This is where you really need to use stock assessment tools.

Table 6. Ability of the different FMSP tools to provide advice on different management measures

Management measures	Biological studies	Yield	CEDA	ParFish	Empirical methods	Beverton and Holt invariants
Fishing effort ('input') controls, e.g. limited vessel licensing		●[1]	●	●	●[2]	●[1]
Catch ('output') controls, e.g. quotas or 'TACs'		●[3]	●	●	●[2]	●[3]
Closed seasons	●	●			●[4]	
Changing size at first capture (e.g. with minimum legal mesh size or fish size regulations)	●	●			●[4]	
Closed areas	●			●	●[4]	

[1] *In combination with LFDA or some other method of estimating current fishing mortality rate.*
[2] *Per unit area.*
[3] *If biomass is also known.*
[4] *Based on comparisons with other fisheries or sites using these management measures.*

And which tools could I use for short-term, tactical assessments?

If you are making a tactical assessment, you will already have decided your management measures and agreed your reference points. You then just need to estimate your selected indicators to see if you are meeting your targets (or keeping clear of your limit reference points), and provide advice accordingly.

As shown in Table 5, if you have chosen to use biomass-based reference points, you could use CEDA or ParFish to estimate the current stock size and be sure it is safely above the MSY level, plus any adjustment to allow for precaution or risk (see Chapter 5 below).

If you have decided to use *F*-based reference points, you need to estimate *F* each year (or every few years) as the key status indicator for the fishery. You can use LFDA to estimate the equilibrium fishing mortality rate, F_{eq}. This assumes that mortality rates and annual recruitment to the stock have both been roughly constant over recent years. If your fishery is particularly valuable, you could also consider using 'virtual population analysis' (VPA) to estimate *F* each year (see Box 12).

Box 8. Length Frequency Distribution Analysis (LFDA) software package

What does it do?

The LFDA package estimates growth parameters and total mortality rates from fish length frequency distributions. The parameters of the 'von Bertalanffy' growth model are estimated as the best fitting curve through the 'modes' in the length frequency data (see Annex 3). Having estimated the growth curve, three different methods may then be used to estimate the total mortality rate, *Z* (see FTP 487, Section 4.1).

What data does it need?

The software works best with a time series of length frequency samples, e.g. collected every other month, for a full year. Samples should be selected from fishing gears that are relatively non-selective, i.e. that catch both large and small fish. Good length frequencies from such gears should show a seasonal progression of modes as fish grow through the length classes. Although a growth curve can be fitted through just one or two samples, a time series of several samples should give better confidence that a real growth curve has been detected.

What advice can it provide?

The growth parameters from LFDA are used as intermediate parameter inputs in the analytical SA approach e.g. using the Yield software (see Annex 3).

The average fishing mortality rate over recent years, F_{eq}, can be used as an indicator of fishing pressure, allowing comparisons with Yield's *F*-based reference points in tactical stock assessments. F_{eq} is obtained by subtracting the estimated natural mortality rate, *M* from the *Z* estimated by LFDA. *M* can be estimated from the growth rates e.g. in Yield.

Box 9. FMSP 'Yield' software package

What does it do?

The 'Yield' software uses a standard 'analytical' model to estimate yield and biomass-based indicators and reference points, allowing for uncertainty in parameter inputs. Yield predicts both the yield to the fishery and the biomass of the fish stock that might occur at different levels of *F*, and with different closed seasons and size limits (see Annex 3). Both the indicators and reference points can be expressed 'per recruit', or as absolute values (see Box 24 in Annex 3). In the first case, you are assuming constant numbers of new recruits each year, regardless of the size of the fish stock. Absolute estimates are more realistic as they assume that recruitment will fall at low stock sizes, but information is then also needed on the parameters and form of the stock-recruit relationship.

What data does it need?

As an analytical model, Yield requires a range of intermediate parameter inputs to describe the various processes by which fish grow, reproduce and get caught (see Annex 3). Inputs needed include the von Bertalanffy growth parameters, K, L_∞ and t_0; the weight-length relationship parameters, a and b; the natural mortality rate, M; and the length or age at maturity (see FTP 487, Section 4.3). As noted above, the parameters of the stock-recruitment relationship are also needed in order to estimate the most useful absolute indicators and reference points. The uncertainty associated with each parameter may be entered either as a coefficient of variation or a range of values.

What advice can it provide?

Yield estimates the relative values of catches and stock biomass indicators. These can be expressed as actual values, or as fractions of the unexploited levels. These indicators can be used in strategic SAs to examine the relative effects of alternative fishing rates (*F*s), closed seasons or size limits (i.e. different 'scenarios').

Yield also estimates the specific technical reference points (e.g. $F_{0.1}$ or $F_{20\%SSB}$) for your fishery. These will vary according to the values of the different intermediate parameters that you enter for your stock.

From the information you enter about the uncertainties in the input parameters, Yield estimates the corresponding uncertainty in the indicators and reference points. Confidence intervals based on this uncertainty can be used to provide advice on what level of adjustment should be made to the reference points to ensure 'precautionary' management (see Chapter 5 and Box 16). Yield also enables you to estimate the 'transient' reference point showing the actual risk of falling below an undesirable spawning stock size at which recruitment may decline (e.g. 20% of the unexploited level).

Box 10. Catch and Effort Data Analysis (CEDA) software package.

What does it do?

CEDA analyses catch and effort data to provide estimates of the current and unexploited fish population sizes, the catchability of the fishing gear, and other intermediate parameters. It fits both 'depletion' models, and several types of biomass dynamic models, which make different assumptions about recruitment, leading to different basic shapes of the biomass-production curve in each case. Three commonly-used variable-recruitment production models (the Schaefer, Fox, and Pella-Tomlinson models) are included within CEDA.

The production models are fitted using non-equilibrium methods, and so the assumption that the data come from a stock at equilibrium is not made here. Three different error models may be used (normal, log normal and gamma), and advice is given in the package on how to find the best fit. An example CEDA analysis is shown in Annex 4.

What data does it need?

CEDA requires a multi-year time series of catch data, and abundance data (either commercial CPUE data, or research survey data). The catch data must be available over the whole time period to be analysed, but the abundance data need not be.

What advice can it provide?

CEDA provides estimates of the current and unexploited fish population sizes, catchability (q), and intermediate population dynamics parameters (r, K). It provides point estimates, and can also generate confidence intervals around these. With the production models, these intermediate parameters can be used to estimate 'MSY' reference points for catch or effort.

CEDA can also be used to evaluate different management strategies, by projecting the stock size into the future under various scenarios of catch or effort.

Box 11. Participatory Fisheries Stock Assessment (ParFish) software package.

What does it do?

With the ParFish software, you can fit the Schaefer biomass dynamic model using historical catch/effort/abundance data (as in CEDA), and/or a range of other information sources. The software uses a Bayesian approach to combine such different data sources, integrating the uncertainties in each. It provides management advice based on the probabilities of specified outcomes for alternative management scenarios, involving catch and effort controls and closed areas. Further details on the method are given in Annex 5.

The software is still under development, with the focus on making the method easier to use and more accessible to fisheries scientists charged with assessing small scale fisheries where extensive data collection and monitoring are not possible.

What data does it need?

ParFish can use the same catch, effort and/or abundance data as used by the Schaefer model in CEDA. Other information such as 'priors' for the model parameters, or from fishing experiments, can be combined with the catch/effort data to improve the analysis. Where no catch/effort data are available, data from interviews with fishermen can also be used to estimate the model, as a starting point for an adaptive management system. As with the analytical approach, ParFish can thus be used to give initial advice even when only limited historical information is available. Initial estimates of the target and limit reference points can then be updated in future as new data are collected.

The method can also use interview data on stakeholders' 'preferences'. This can help in deciding the 'optimal' management actions, and may encourage acceptance of management measures in a co-management situation.

What advice can it provide?

The software is designed to estimate the intermediate parameters of the Schaefer production model, and thereby provide guidance on effort control, quotas or refuges (closed areas or reserves). With its production model basis, ParFish estimates 'MSY' reference points for catch or effort. With its Bayesian formulation, the advice provided fully accounts for the uncertainties in the assessment, and the risks of exceeding biological limit points.

Box 12. What is Virtual Population Analysis (VPA)?

VPA methods use time series of input data on the total catches in each age class to estimate both the stock size and *F* in each year and each age class. VPA methods are thus very useful in producing both biomass and fishing rate indicators and form the backbone of fishery management systems for many of the world's most valuable fish stocks. The results from VPAs can help you to understand the relationship between stock size and recruitment, and estimate some of the more advanced 'absolute' reference points (see Table 5). They are, however, also very data hungry, requiring large scale catch and length frequency sampling and routine ageing of fish for 'age-length keys'.

3.3 What should I do in a multi-species situation?

Multi-species fisheries and the biological interactions within them (such as competition and predation) are complex and not clearly understood. Most multi-species models that attempt to allow for biological interactions are complex and data-hungry, and therefore inappropriate where resources are limited.

One tool you could consider for the analysis of the simpler 'technical interactions' between fishing gears is the multi-species, multi-gear YPR model developed by Sparre and Willmann, (1992) as 'BEAM4'. A version of this model allowing up to 19 species (or guilds) and 12 fishing gears (fleets) is now available as the Thomson and Bell yield prediction model in FiSAT. This analytical model estimates the total yield available from the multi-species complex, allowing for the different size selectivities and seasonalities of the gears, etc. Although the data requirements are high, the model may be used to investigate the effect of mesh sizes, gear bans and closed seasons as well as changes in fishing mortality rates. This model was used in DFID project R4791 (see Hoggarth & Kirkwood, 1996).

Multi-species fisheries can be assessed using more complex analytical models (with higher data needs), or by using indicator species, or by lumping all of the species together as one overall 'stock'

FMSP project R5484 showed that single-species models can also be used to provide useful management advice in multi-species situations (see Section 4.4 and Chapter 12 in FTP 487). The project developed guidelines for management of multi-species fisheries, and for evaluating the status of those resources, using reference points available from other stock assessment tools such as Yield. These guidelines describe ways of selecting the most important and vulnerable species for analysis (the key indicator species), and give a method for setting overall effort limits that would protect the most vulnerable species, if that was the objective.

The R5484 guidelines relate to bank and deep reef-slope fisheries for demersal species caught with hooks and lines. They relate mainly to the use of *F*-based management since other approaches would be impractical for these fisheries (fish sizes are difficult to control for example). The optimum *F* depends largely on the size at first capture relative to the size at maturity and the asymptotic length, L_∞.

Finally, you should consider using the 'empirical' fishery modelling approaches developed by FMSP project R7834, and described in Chapter 14 of FTP 487. These approaches analyse the potential productivity of your fishery, and the likely success of different management measures, based on comparisons with other similar fisheries elsewhere. They are likely to be particularly useful for fisheries that can be sub-divided into small spatial units, such as individual case study villages or lakes within a river catchment, or sections of coastline. They allow you to examine the effects of management measures applied in certain of the units, while allowing for other 'external' impacts which may also be affecting the state of each fishery.

4 How do I select the best tool for the job?

We suggest you use a two step process to select your stock assessment tools.

Step 1. What tools can provide advice about the management controls and standards (indicators and reference points) selected for the fishery?

Step 2. Of the tools and approaches available, what is the most appropriate to the local situation?

4.1 Step 1 – Which tools could I use?

The choice of tool depends on how the objectives will be measured, and on what management measures are feasible – if data are not available to use these tools, you should start to collect them now and apply precautionary measures in the mean time

The choice of tool should start with an understanding of the management objectives, and the indicators and reference points that are selected as management standards for each objective. These will dictate which tools could be appropriate. If data do not exist to apply those tools, then a programme of data collection should be initiated. This is better than working the opposite way of starting with the available data and saying what is feasible (though this may be necessary in the beginning).

In the previous chapter, we discussed which indicators and reference points can be derived from each of the FMSP tools (see Table 5). We also looked at which tools can give advice about which management measures (see Table 6). When you have agreed the objectives and management measures with your managers, potentially useful tools may be identified from those tables. Also bear in mind that the FMSP tools do not cover all the possible reference points and that other options are available.

4.2 Step 2 – Which tool would best suit our circumstances?

Having looked at the options in Step 1, you will often find that more than one tool may provide the same indicators or reference points, or address the same objective. You then have to make a decision as to which of the possible options to use. Summary comments on the pros and cons of the different stock assessment approaches and tools are given in Table 7 and Table 8 respectively. If your fishery is particularly valuable, you could of course try out several different assessment methods to try to improve your knowledge on the fishery and reduce the risk of problems.

Where resources are limited, you will also need to consider carefully the choice of management control. Do you have enough capacity, for example, to implement catch quotas? Or would effort controls be more feasible to monitor and enforce? Once again this highlights the need for managers and stock assessment staff to work together closely in developing the management plan.

Table 7. Summary comments on the alternative modelling approaches (see also Table 5 and Table 6, and FTP 487, Section 3.1)

Stock assessment approaches	**Advantages / application**	**Disadvantages / comments**
Length based (e.g. LFDA)	• Fitting of growth and mortality rates directly to modes in length-frequency data without the need for age-determination of individual fish· • Lower data needs and costs • Useful for species that cannot be aged (e.g. some crustacea or tropical fish)	• Lower accuracy and precision than age-based methods • Some methods only useful for certain types of species (e.g. growth methods better for fast growing species) • Sampling may be highly biased by selectivity of fishing gear or behaviour of fish, e.g. not feasible with gill net fishery
Age based (e.g. by ageing otoliths)	• Higher accuracy and precision • Use wherever fish can be aged	• Higher data needs and costs (for ageing fish), but may still be more cost effective in the long run
Biomass dynamic approach (e.g. in CEDA or ParFish)	• Simple to apply • Only catch and effort or abundance data needed • Useful for species that cannot be aged • Can use aggregated model for multi-species fisheries	• Requires a long time series of data (several years) • Advice may have high uncertainty where data contrast is low • Requires a good index of abundance (e.g. CPUE) with constant catchability, *q*
Analytical approach (e.g. Yield with LFDA)	• Useful when different fleets exploit different age groups • Management advice can be provided with only one years' data	• High data costs and analytical needs • Advice may have high uncertainty, mainly because of high uncertainties in estimates of Z and M.
Bayesian methods (e.g. in ParFish)	• Useful where information on the fishery is limited (e.g. short data series, little contrast etc) • Allows inclusion of 'auxiliary' data or knowledge that improves the assessment • Allows for the integration of multiple uncertainties to assist decision making	• Higher complexity· • Need some understanding of Bayesian statistics to apply • Is likely to have high uncertainty where information is limited. • Yield prediction methods provide approximate results, based on observations at other sites, assuming resources and

Empirical approaches (see FTP 487 Section 4.7)	• Models provided to estimate potential yield per unit area and optimal fisher densities for floodplain rivers, lakes and reservoirs, and coral reefs • Time series of catch and/or effort not required • General Linear Modelling (GLM) and Bayesian Network methods examine the effectiveness of management measures and other factors on fishery indicators • useful for understanding causes and effects within complex fishery systems • Useful where fisheries can be split into independent sub-units, for testing different management measures in each • Designed to enhance learning process for adaptive co-management	exploitation patterns are similar • Multivariate modelling methods (GLM and Bayesian) require detailed studies from case study fisheries / villages (independent units) with some contrast in the variables of interest

Table 8. Summary comments on the alternative FMSP stock assessment tools and some alternatives (see also Table 5 and Table 6, and FTP 487, Chapter 4)

Assessment Tools	Advantages /application	Disadvantages / comments
LFDA	• Estimates growth and mortality rates • Useful where fish can not be aged • Only needs length frequency data	• Accuracy of parameter estimates may be lower than age-based alternatives
Yield	• Estimates *F*-based reference points allowing for uncertainties in inputs • Outputs include probability distributions for indicators and reference points, enabling estimation of precautionary buffers • Can includes stock recruitment inputs to enable yield/biomass outputs as well as YPR/BPR • Includes projection facility • Estimates 'transient' risk-based reference point allowing for variability in annual recruitment	• Not formulated for economic or multi-species, multi-gear analyses

FiSAT (an alternative to LFDA and Yield)	• Also uses length frequency data • More model forms available • Also able to estimate economic reference points • Allows multi-species, multi-gear models ('BEAM4')	• No consideration of uncertainties or confidence intervals for outputs • SRR not included
CEDA	• Use 'no recruitment' models to estimate abundance over a short depletion experiment or single fishing season. • Use biomass dynamic models to estimate stock size and MSY for longer time series • Useful diagnostic tools (residual plots and goodness-of-fit) • Includes projection facility • Estimates distributions of parameters (and confidence intervals) by bootstrapping	• Limited to six model forms (plus three different error models) • Does not allow analysis of multi-fleet data sets (data may need to be standardized first for analysis)
ParFish	• Can begin management with no previous data, e.g. by using instead the local ecological knowledge of fishermen or other experts • Can improve analysis with 'prior' information from other stocks, or localized depletion experiments • Can include 'preference' data from fishers and managers to assist decision analysis • Designed to assist co-management of small and medium scale fisheries – may improve acceptance of management rules	• Only logistic (Schaefer) model available • Most applicable to discrete stocks whose boundaries relate to the boundaries of the community (e.g. small lakes or enclosed coastal bays)
Beverton & Holt 'invariants' method	• Useful for estimating reference points where only limited data are available (need only K and L_c for simplest version)	• Limited range of reference points available (but including F_{MSY}) • Need to assume standard growth patterns
Empirical approaches (see FTP 487 Section 4.7)	• GLM approach suitable for examining the impacts of multiple independent variables on *quantitative* fishery indicators • Bayesian approach analyzes relationships among multivariate data sets including *qualitative* variables	• Require detailed studies of both indicators and potential influential factors for several sites to enable comparisons

In addition to considering the pros and cons of the different tools available, and their relevance to both your particular fishery and the agreed objectives, a number of other factors may guide the selection of tools. A process for considering these is given in Box 13. To decide which tool to use, we suggest that you work through this process and compile the information in a table such as the one given in Table 9.

Box 13. Factors to consider in selecting appropriate stock assessment tools

1. The choice of tool starts with an understanding of the management objectives for a particular fishery, and the selection of relevant management standards (indicators and reference points).
2. Next consider what inputs (data) are required to use these tools and answer specific management questions relating to the objective. The data needs of the different FMSP tools are given in the boxes about each tool (see also Section 2.3 above, and Tables 5.1 and 5.2 in FTP 487). Other data collection may be required to address socio-economic needs or to address specific biological questions such as the location and season of spawning aggregations. Specific directed research activities may be needed to supplement the regular programme of data collection for stock assessment.
3. What data already exist, and what level of analysis can immediately be achieved with this information, and using which tools? What precautionary advice could you give at this stage and does this affect the definition of management control rules or highlight issues relating to a particular objective?
4. What additional data should be collected to complete a stock assessment using the tools available (and over what timeframe must it be collected for it to become useful)? What additional data are required to address the other needs identified in (2) above?
5. What is the current institutional capacity and what resources are available to collect the information required? What additional data collection is immediately feasible given current capacity and what additional resources must be obtained before adequate data collection is possible? Does this refine the choice of tool that can feasibly be used?
6. Finally what are the costs and benefits of different models? There are a number of elements to this:
   - The costs and benefits in terms of the ability to make good assessments in a given time frame. Table 7 and Table 8 list some of the costs (disadvantages) and benefits (advantages) of the different approaches tools, and may help to guide selection.

- The actual costs of data collection relative to the institutional capacity and resources of the fisheries department. These costs need to be balanced against the benefits of management. Benefits are directly related to the goal and objectives to which they relate and can be expressed in terms of those goals. For example, if the goal is to maximise employment opportunities, the benefits can be quantified and related to the number of people expected to benefit from improved fisheries management. These benefits are likely to outweigh the costs and may justify the allocation of additional resources.

Having completed the steps in Box 13, and summarised them in a table like Table 9, the information should be discussed with your managers to derive a recommended course of action. In addition to helping you select the best tools, this process may show which management standards are immediately sensible for the fishery, and which ones would be desirable for the future. This will show you which tools you could use immediately and which ones you could use in future if appropriate data collection programmes are set up. The analysis could also be used to justify requests for additional resources to initiate the recommended data collection.

Table 9. A suggested template for comparing stock assessment tools and providing advice on which tool to use

Objec-tives	Possible manage-ment standards and measures	Rele-vant tools	Input require-ments (data etc)	What data are already available and what pre cautionary advice could be given with this?	What resources are needed to collect additional data to complete stock assessment?	Costs and benefits of different tools and data collection needs

… Add more rows as necessary to cover all the objectives and tool options

5 How should I provide stock assessment advice to managers?

There are various options for presenting advice to managers, for example, written reports or computer presentations using either graphs or tables, or both. You should ask your managers which formats they prefer. Whatever they request, results should always be presented in a logical, clear and consistent manner.

Where stock assessments are written up as a full report, this should give details of the analyses done, including the models and data used, and any assumptions made. You could also provide a summary briefing in written or presentation form. The full report can then serve as a supporting document to the summary.

The format of such managers' briefings will vary according to the nature of the fishery, and the purpose of the assessment. A report from a full strategic stock assessment should assist the design of the management plan by answering the following questions:

- "*Where would we like to be?*" – the values of specific reference points selected by managers, as estimated for that fishery, updated for any new data (e.g. the actual value of F that would give MSY, e.g. $F_{MSY} = 0.4$).
- "*Where are we now, relative to where we would like to be?*" – an assessment of the current status of the fishery as given by the indicators (e.g. the estimate of F_{now}).
- "*What are the implications of alternative management scenarios, including doing nothing?*" – estimates of the effect on each indicator of those management measures or controls identified as feasible for the fishery.

A report from a tactical stock assessment, may be provided every year or two to monitor the status of the fishery and guide the adjustment of any management controls. This would focus more on the '*where are we now*' indicators, and their position relative to the reference points. As required by managers, guidance on alternative management scenarios could also be provided, depending on whether a strict decision control rule system has already been adopted.

You will always have some uncertainties in your stock assessments which will need to be managed with precaution

In any stock assessment, you will always have some degree of uncertainty in the results you obtain. While uncertainties have often been ignored in the past, the precautionary approach now requires that you estimate the risks associated with the various uncertainties, and that your managers choose management measures and strategies that take those risks into account. You will have uncertainties both in the data you use and in the biological, economic and social processes in the real world, and as assumed in any models. While the depth of the analysis may vary in data-rich and data-poor assessments, these uncertainties should always be carefully considered. The following sections, then, briefly describe how you should brief managers on their options allowing for the uncertainties and risks involved.

5.1 Providing strategic advice on alternative management options

In strategic assessments, alternative management scenarios are usually compared to a 'baseline' scenario, which might be, for example, to carry on as currently (i.e., taking no management action, or making no changes to the existing controls and enforcement activities), or to take an 'optimal' scenario of fishing at the target level. Since an immediate change in fishing to the 'optimal' level may not be feasible, scenarios can also be used to investigate how fishing at various other levels would affect the stock.

e.g. If, for example, current fishing pressure is 30% above the target level, but an immediate reduction to the target level is not considered feasible by managers (due to the socio-economic consequences), alternative scenarios could investigate the consequences of reductions in fishing to say 20%, 10% (and 0%) above the target, or a phased reduction.

In the simplest case, you could provide advice on the expected level of a single indicator (e.g. '%SPR' - the level of spawning 'per recruit', relative to that in an unexploited stock) for different levels of a single management measure (e.g. adjustments to fishing effort, estimated as the fishing mortality rate, *F*). In this case, you could show either a simple graph or a table to present the results.

Using graphs to present results for each indicator

Where more than one objective is selected, as will usually be the case, you will need to show the trade-offs between different indicators by plotting

Graphs or decision tables may be used to show the trade-offs between objectives for a range of management options

separate graphs for each indicator (e.g. for both the %SPR and the yield per recruit or YPR). Such graphs should assist in the selection of a precautionary management strategy by identifying the relative positions of alternative reference points (e.g. setting a limit reference point of 20-30 %SPR, and a yield-based target reference point at $F_{0.1}$ or similar). If you have reason to believe that CPUE is broadly proportional to biomass in your fishery, the %SPR curve may also be examined as an index of the likely catch rates and the fishermen's incomes. You could mark the current levels of the indicators and the reference points on such graphs (see for example the right hand plot in Figure 9 in Annex 3).

Graphical methods are thus useful for presenting results from stock assessments especially where the number of possible management measures is only one or two. If alternative levels of two management measures are being considered, a three dimensional graph can be used such as the classic YPR 'isopleth' diagram, in which contours of yield are plotted against fishing rates and mesh sizes. Where there are two or more indicators (e.g. both yield and SSBPR), several such graphs can be viewed to determine regions of parameter space that are acceptable for all of the indicators. The constraint in such a graphical approach is the number of axes. With three or more management measures, and two or more objectives (criteria or indicators), a decision table approach may then be used as described below, or more quantitative methods of optimisation may be considered (see Hilborn and Walters, 1992, chapter 16).

Using decision tables when it gets more complicated

A good decision table will remind managers of the inevitable trade-offs between different objectives

When there are several management options and several objectives to be evaluated, you can also use 'decision tables' to present information in a form that facilitates comparison and shows the trade-offs involved in the different options. A well-structured and complete decision table will not only summarise and present key results from the analyses, but can also serve to remind the decision-makers of their objectives.

Box 14 shows the use of a simple decision table format which could be extended to evaluate a larger number of management scenarios (columns) for a larger range of indicators (rows). You might notice that this illustration of a strategic stock assessment does not refer to any reference points. Where specific reference points have already been selected (such as 20% SPR, or B_{MSY}), the expected values of the indicators (SPR or *B* in this case) can also be presented in the tables as percentages of those reference points.

e.g.

Box 14. Example presenting strategic assessment results as a decision table

In this theoretical example (which might have been based on a 'Yield' analysis), the current spawning stock biomass per recruit (%SPR) is estimated to be only 20% of the unfished level, as shown in the top left results cell. Allowing for the uncertainties in the assessment, however, it could be as low as 11% (shown by the lower confidence interval given in the brackets). Levels of %SPR of 20-30% are commonly regarded as safe lower limits for maintaining a large enough breeding population of fish and long term recruitment to the fish stock (see FTP 487, section 3.5.3). In management scenario 2, a reduction in fishing mortality of 20% (e.g. by gradually reducing the number of fishing vessels by 20%) is predicted to increase the %SPR to a less risky mean level of 30%. It would also slightly reduce the total yield per recruit in the fishery (which may be assumed to be proportional to total yield in the absence of more detailed information), but would slightly increase the mean catch per fisher. In scenario 3, a 20% increase to the mesh size limit would benefit each of the biological and economic indicators, without the negative social impact of the effort reduction.

Cochrane, (2002) provides another example of a decision table (his Table 5 in Chapter 5), showing the types of trade-offs that may present managers with some difficult decisions.

Implications of three fishing effort scenarios for selected fishery indicators

	Management Scenario 1 (No change)	**Management Scenario 2** e.g. *F* down 20%	**Management Scenario 3** e.g. mesh size limit up 20%
Biological Indicators e.g.Relative spawning per recruit (%SPR)	20 (11 – 29)	30 (20 – 40)	35 (26 – 44)
Economic Indicators e.g.Relative yield per recruit (%YPR) Mean catch value per fisher ($ '000)	13 (10 – 16) 5 (3 – 7)	12 (9 – 15) 5.8 (3.8 – 7.8)	14 (11 – 17) 5.4 (3.4 – 7.4)
Social Indicators e.g.Change in number of fishers	0	-20%	0

Note: values in parentheses are 95% confidence intervals.

Strategic assessments can thus be used to investigate the effects of different management measures or strategies on catches, stock biomass, and the risk of stock collapse. In most cases, no single strategy will maximise all the potential benefits and minimize all the potential risks. The effect of each scenario on each performance indicators should therefore be shown in the decision table as above. Strategic SAs should always somehow include information on the risk of stock collapse (for example, as indicated by the SPR being reduced to below 20% of unexploited levels). If this does occur, there will be no catches, employment or income from the fishery while the stock recovers. Further guidance on this is given in Section 5.5.

In most cases, no single strategy will maximise all the potential benefits and minimize all the potential risks

5.2 Providing tactical advice to guide management by the control rules

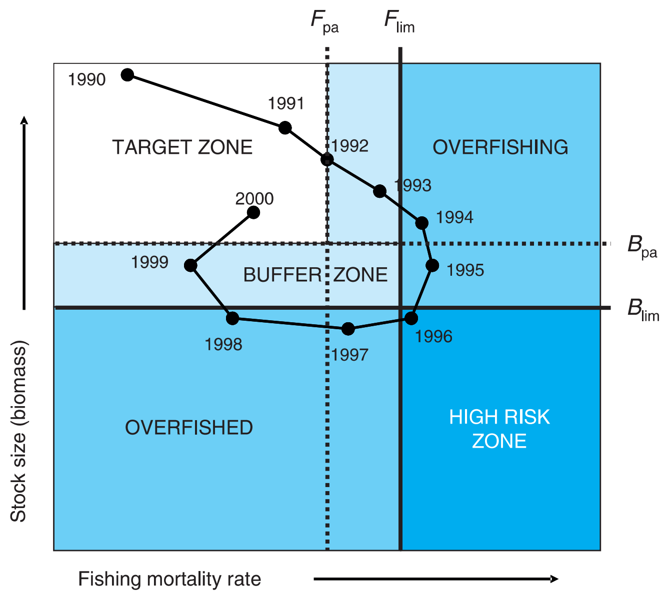
Where the 'harvesting strategy' and the 'decision control rules' for the fishery have already been agreed with stakeholders (see Managers Guide), you will need to provide annual advice on the levels of the chosen indicators relative to their specific reference points. One way of showing the status of your fishery over time is illustrated in Figure 3 in the following page.

Tactical advice is used in monitoring the fishery by comparing the current levels of the indicators with the reference points

Your managers will use this 'tactical' SA advice to consider what adjustments could be made to the management controls to keep the fishery within the bounds set by the reference points. Such adjustments should have been defined at the plan development stage, and specified as decision control rules.

e.g. The control rule example in Figure 4 illustrates the case where biomass-based indicators and reference points can be estimated and where the fishery is managed to maintain the stock above a certain limit biomass (e.g. B_{MSY}). In this case, managers should be provided each year with estimates of B_{lim} and the precautionary reference point, B_{pa}, along with B_{now}. These would then be used to set the next year's fishing mortality F_{NY} according to the agreed control rule (i.e. at or below F_{pa} depending on B_{now}). If B_{now} is below B_{pa}, then the stock should be regarded as approaching an overfished condition. In that case, whether adjustments are required to next year's fishing mortality, F_{NY} would depend

Decision control rules define what management actions will be taken depending on the levels of the indicators (relative to any target, limit or precautionary reference points)



e.g. Figure 3. An example plot showing the status of a hypothetical fishery monitored over time for both stock-related and fishing-related indicators. The points show the history of the fishery over the years 1990 to 2000. In this example, the fishing pressure became too high in the mid 1990s, rising first above the precautionary reference point, F_{pa}, and then above the limit reference point, F_{lim}. The stock size then declined to an overfished state below both B_{pa} and B_{lim}, but recovered to the safe 'target zone' when the fishing rate was reduced (source: redrawn with permission from Garcia, 2000 and FTP 487). Note that the precautionary fishing rate, F_{pa} (dotted line) is less than the limit fishing rate, F_{lim} (solid line), while the precautionary biomass, B_{pa} is greater than the limit biomass B_{lim}.

on the probability of returning to a healthy stock state (given expected average recruitments), and hence on the current level of F compared to F_{pa}. If F_{now} is less than F_{pa}, the low state of the stock may be due to a chance occurrence of several bad years of recruitment in a row but recovery may still be expected. This could be confirmed by making a medium-term projection as described below. If F_{now} is greater than F_{pa}, regardless of the state of the stock, it should be reduced according to the control rule to reduce the chance of the stock becoming overfished (if it is not already).

If only F-based indicators and reference points are available, as may be the case in some data-limited fisheries, management actions can be based only on these points. If F_{now} is above F_{pa}, then this should be interpreted as overfishing. Adjustments should then be made to F_{NY} as required, according to the degree of overshoot. In this case, fishing mortality is conceptually on both the x-axis (F_{now}) and the y-axis (F_{NY}) of a control rule plot.

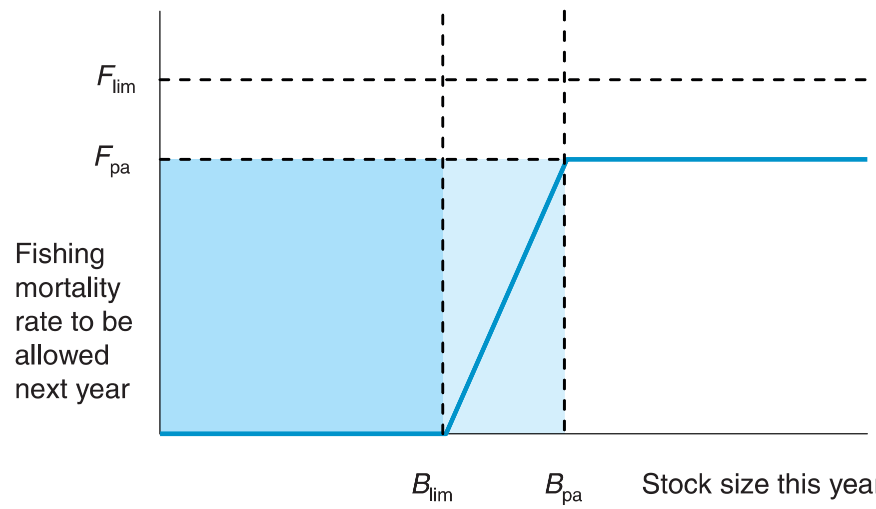


Figure 4. An example decision control rule framework with limit and precautionary reference points and a constant exploitation rate harvesting strategy (set at F_{pa}, where the current B_{now} is greater than B_{pa}, and declining gradually to zero as B_{now} approaches B_{lim}). See also the similar versions given as Figure 9 in the Managers Guide, and as Figure 2.6 in FTP 487. Note that the axes in this figure are switched from those in the previous one (Figure 3). This is because in the previous plot, the state of the fish stock (biomass on the y-axis) is presented as the *result of* the fishing rates applied (*F* on the x-axis). In the decision control rule here, the fishing rate next year (on the y-axis) is set *according to* the current state of the stock (on the x-axis).

5.3 Making projections: how long will it take to achieve the results?

In both strategic and tactical assessments you may also brief managers on how long the suggested management measures might take to have an effect. This will depend on the age structure of the fishery (how many years it will take for all of the age classes to reach equilibrium at a new *F* level), and of course also on the future recruitment and the current size of the stock. We use 'projections' in stock assessments to evaluate the trade-offs in the actions taken to protect the stock and the length of time it will take for the stock to respond. Projections are recommended by FAO (1997) as one element of responsible fishery management.

Long term projections are used to predict which management options would achieve the plan objectives, and how long each one would take.

Short term projections are often used to estimate next year's catch quota from this year's biomass

Such projections form the basis of 'rebuilding plans' for overexploited fisheries. Given the uncertain influence of, in particular, the actual levels of future recruitment, the future clearly cannot be predicted exactly. As with other models, though, you can show decision makers the relative trade-offs and risks of alternative strategies, at predicted average levels of recruitment.

Projections can be made using a range of models, including both analytical and biomass dynamic forms. They are most useful where the current state of the stock is known reasonably well and is used as the basis for the prediction of the future states. In the FMSP CEDA software (see Annex 4), current biomass is estimated and the likely future trajectory of the stock may then be estimated for different scenarios of fishing effort or catches. With the 'Yield' software (Annex 3), the current biomass will often not be known, but projections can still be made of the relative future stock sizes at different future levels of *F*.

You might make short, medium or long-term projections. A short term projection might look 2-3 years into the future and a medium one 5-10 years for a fish species of average longevity. A long-term projection should demonstrate the equilibrium state (as assumed in Box 14). It could also include uncertainties in both model parameters and year to year fluctuations in recruitment (as in the 'Yield' 'Transient' reference points – Section 5.5). Short term projections are mainly used for calculating a total allowable catch (TAC) in the next year, reflecting the current size of the fish stock and the fishing fleet. Medium-term projections are used to show the most likely consequences of setting TACs over the next few years (will a given TAC allow the stock to re-build, and in how many years?; or will it lead to a decline?). Long-term projections show the eventual position of the policy relative to the reference points.

5.4 How should I present the uncertainty in my analysis?

You will always have some uncertainty in your assessments, and it is very important that you get this across to your manager. Some types of uncertainty can be allowed for by using a particular stock assessment tool. Yield, for example, shows you the importance of *parameter* uncertainties on your results. Where there are also different possible *model* forms or other 'hypotheses' (see Box 15) you should repeat the analysis for each one and then present all the different results to the manager.

The uncertainty in your stock assessments must be communicated to the manager, e.g. using confidence intervals or histograms

Box 15. What is uncertainty?

Uncertainties in the estimates of parameters in fishery models depend on the variability of natural processes, the quality and quantity of data collected and the fitting methods used. The high variation in annual recruitment to a fish stock for example reflects the various environmental factors that exist in the real world but which are ignored in most stock-recruitment models. Measurement errors exist wherever sampling is used to estimate a parameter. While *precision* (the confidence we have in the estimate) may be increased with larger sample sizes, *accuracy* (the closeness to the true value) may still be low if the sampling procedure is biased in any way.

Uncertainties also exist in the processes that are included in the fishery models, such as the shape of the biomass-production function (Schaefer or Fox form), or the growth pattern of the fish (von Bertalanffy or other form). In precautionary analyses you should test such 'alternative hypotheses or states of nature' (FAO, 1996) to see the effects on the results, rather than simply assuming that one single model is correct. Uncertainties may also exist in the operation or management of the fishery (e.g. systematic under-reporting of catches or discards; or non-constancy in the catchability coefficients). While uncertainties in parameter estimates may be seen as having a probability *distribution* (e.g. a mean with a defined error distribution and confidence interval), uncertainties in hypotheses or states of nature are more often *discrete* possibilities (e.g. the Schaefer and the Fox production models are two alternative model hypotheses).

For simple ways of explaining the concepts of uncertainty, see 'Concept 4' in the ParFish Guidelines produced by FMSP Project R8397 (see http://www.fmsp.org.uk/r8464.htm).

Different SA tools present uncertainty in different ways. Some produce point estimates, with the uncertainty around these illustrated by a confidence interval (see Box 16). Confidence intervals from the Yield software are shown by the dotted lines in Figures 4.2 and 7.1 in FTP 487.

Box 16. Using confidence intervals to express uncertainty

A confidence interval (CI) is the range of values between which there is specified probability that the true value lies. For example, a 95% CI is the range of values between which there is a 95% probability that the true value lies. Conversely, this means that there is a 5% probability that the true value lies outside this range, either above or below.

For example, if the estimate of MSY is 370,000 MT and the 95% CI is (120,000 MT, 520,000 MT), then there is a 95% probability that that the true value is within the range 120,000-520,000 MT. Outside this CI, there is 2.5%

chance that the true value is below 120,000 MT and a 2.5% chance it is above 520,000 MT.

What size interval is chosen depends on the level of risk (that the true value is outside the CI) that is agreed as acceptable. A 99% CI will give the range where there is only a 1% chance that the true value lies outside. However, increasing the degree of confidence (say, choosing 99% CIs instead of 95% CIs) will increase the size of the range and therefore have significant implications for any reference points that are being estimated.

For further information on CIs, see Section 8.2.7 in FTP 487.

Both Yield and CEDA also present the uncertainties in results as histograms (e.g. as in **Figure 5**, below, and Figure 4.7 in FTP 487). The uncertainty represented in **Figure 5** could be presented to managers as follows:

e.g. *In this Yield analysis, the top two graphs show that the maximum sustainable yield (MSY) of about 1400t may be achieved at a fishing mortality of about 0.47. However, in 5 out of the 100 simulations, the fishing mortality which achieved MSY was only 0.24, and in 4 of the 100 simulations, the MSY was estimated as only 600t.*

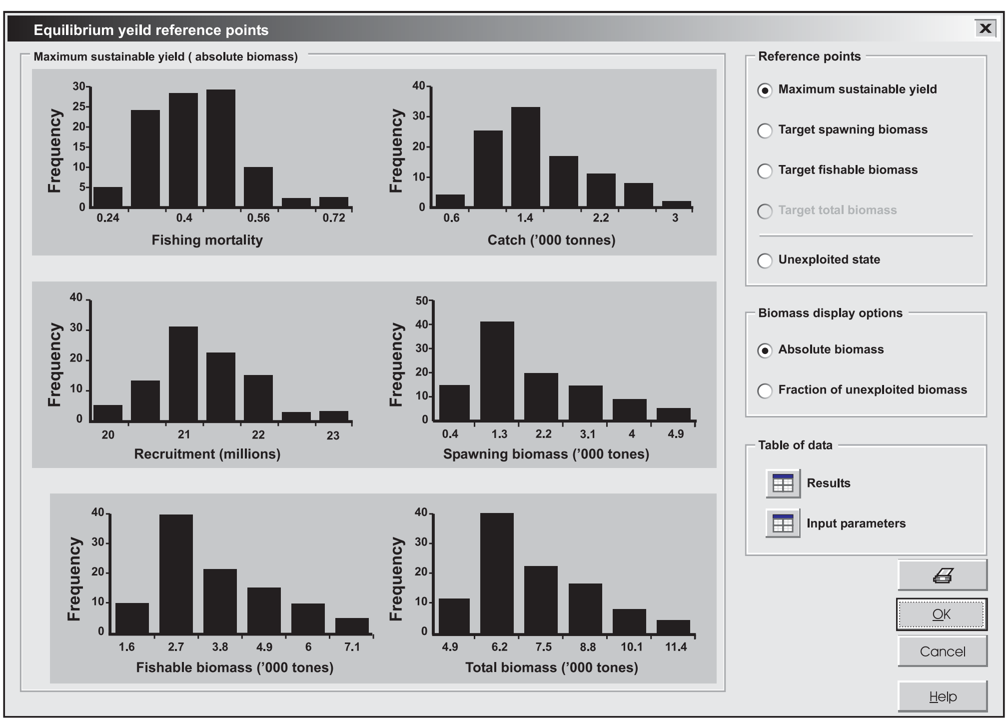


Figure 5. Example output from the Yield Software showing the uncertainty in the MSY reference points

You should also remember that the uncertainty estimated by such confidence intervals or parameter distributions may represent only part of the total uncertainty in the analysis. As mentioned above, this also depends on the assumptions made and the models that have been used. More realistic confidence intervals should thus be calculated by testing out a range of input values or model forms as described below.

Uncertainty will exist in both the accuracy and precision of the model parameters and in which model is most appropriate for your fishery

Sensitivity analysis - testing the effect of uncertainties in the analysis

In a 'sensitivity analysis', you try out alternative values of input parameters or model assumptions to test their influence on the results of the analysis. You can also test the sensitivity to particular data points or observations. For example, if the survey estimate of abundance from year X was felt to have been measured with particular error for some reason, it could be removed from the analysis to see if it makes a big difference to the conclusions. The software tutorial help files for both Yield and CEDA pay particular attention to the use of such sensitivity analyses.

You will usually present the results of your sensitivity tests as decision tables (like in Box 14). In this case, the rows in the decision table could represent the alternative states of nature or uncertainties. If trade-offs are still being considered for two or more different indicators, multiple versions of the decision tables may need to be produced for each state of nature or major uncertainty.

Sensitivity tests show how much the conclusions depend on the uncertainties

Box 17. What should I do if my sensitivity tests suggest different answers?

This will often happen. If you make separate stock assessments using two or more different sources of data (e.g. CPUE from a research survey and from fishing vessels) they will most likely give different interpretations of the state of the fish stocks. If one of the data sets was biased for some reason, it would not, then, be helpful to just average the two different answers. You therefore need to think carefully why the differences might have occurred. Where there are different sources of the same basic data (perhaps with different assumptions), it is better to present the alternative sets of conclusions to the decision makers along with the assumptions made, to allow them to weigh up the risks.

You can also provide some advice on which of the different tests is more likely to be correct by giving measures describing the 'goodness of fit' of the data to that model form or set of parameters. If it is determined that certain models fit the data much better than others (e.g., a particular error model in CEDA), it may only be necessary to present the best fit. However, sometimes a range of options could be equally valid, in which case all should be presented (see example in Box 18).

e.g.

Box 18. Example - Sensitivity testing of biomass dynamic model forms

The table below illustrates a set of results from fitting two alternative biomass dynamic models in CEDA (the Schaefer and Fox forms) with three alternative error models (least squares, log transformed and gamma) to the tutorial data set for yellow-fin tuna. Although a long-time series of data is available, there is not enough contrast in the data set to be able to estimate *r* and *K* very well (notice the high variability between the six estimates). However, due to the negative correlation between *r* and *K*, commonly found in these models, the estimated MSY can be said to be relatively insensitive to the uncertainties in the model form and error models (notice the much lower variability in the estimates of MSY).

The least squares error model was found to fit the data least well, compared to the log transformed and gamma models. This error model was therefore disregarded. The Schaefer model estimates a slightly lower MSY (149 025 – 158 964 MT with the remaining two error models) than the Fox model (159 981 – 166 608 MT). If no further information is available on which model is the most appropriate, a precautionary manager would adopt the Schaefer model MSY as the lower risk estimate.

Population Model	Error model	*r*	*K* (MT)	*q*	MSY (MT)	R^2	Final *B* (MT)
Schaefer	least squares	0.493	1 306 164	8.155	161 086	0.789	489 169
Schaefer	log transformed	0.317	1 879 579	5.746	149 026	0.861	692 844
Schaefer	gamma	0.459	1 386 679	7.849	158 964	0.825	508 085
Fox	least squares	0.341	1 339 702	8.740	168 306	0.804	485 741
Fox	log transformed	0.224	1 937 359	5.842	159 981	0.873	726 873
Fox	gamma	0.315	1 435 528	8.208	166 608	0.840	518 447

Notes: *r* = intrinsic growth rate, *K* = carrying capacity, *q* = catchability ($*10^{-6}$), Final B = final biomass, R^2 = goodness of fit indicator

Further analysis of this data set would go on to test the sensitivity of the models to the different input parameters, and any possible 'outlier' data points (see CEDA tutorial).

5.5 Giving advice in terms of risk

The main risk is that the fish stock will collapse and you will lose all the socio-economic benefits of the fishery

Risk assessment is one of the foundations of the precautionary approach, and a stated requirement of the UN Fish Stocks Agreement and the FAO Code of Conduct. You need to inform managers about the risks of implementing different management actions both in strategic and tactical stock assessments. From the biological perspective, the most obvious risk is that the stock will collapse. This may happen if the fish stock is reduced below some threshold level, especially if this coincides with one or two years when the environmental conditions are not so good for fish spawning. If the stock collapses, you will of course lose all the socio-economic benefits of the fishery. This section describes different ways you can advise your managers about risks and avoid them.

Risk is formally defined as the probability of something bad or undesirable happening. To assess and manage risks you need to define exactly what is considered 'undesirable' and then quantify the chances of this occurring. In the most complete risk analyses, the risk is defined with the following three factors:

- The threshold it is desired not to fall below (e.g. 20% of the unexploited spawning stock biomass or SSB);
- The probability that this threshold will be broken (e.g. 10%); and
- The timescale over which this may occur (as any event is more likely to occur over a longer timescale than a shorter one) - periods of between 10 and 20 years are frequently used in estimating risks in fisheries.

Each of these three factors should be set by the fishery managers, preferably in discussion with industry stakeholders and other interested parties. As the fishery scientist, you should undertake the quantitative risk assessments, but you should not be expected to advise on the acceptability of alternative risk levels. You can do full risk assessment like this using the 'transient' reference point in the Yield software (see Box 19).

You can also give advice about risks by referring to your confidence intervals. Since these do not include any timescale, this is only a partial risk assessment, but it is still better than nothing (see Box 20).

Your risk assessments can also be presented in the decision tables, for example, by giving both the median estimates of the reference point F_{MSY} and selected lower percentiles from the distribution of estimates (e.g. as provided by Yield in the top left graph in Figure 5) for each 'state of nature' and management measure.

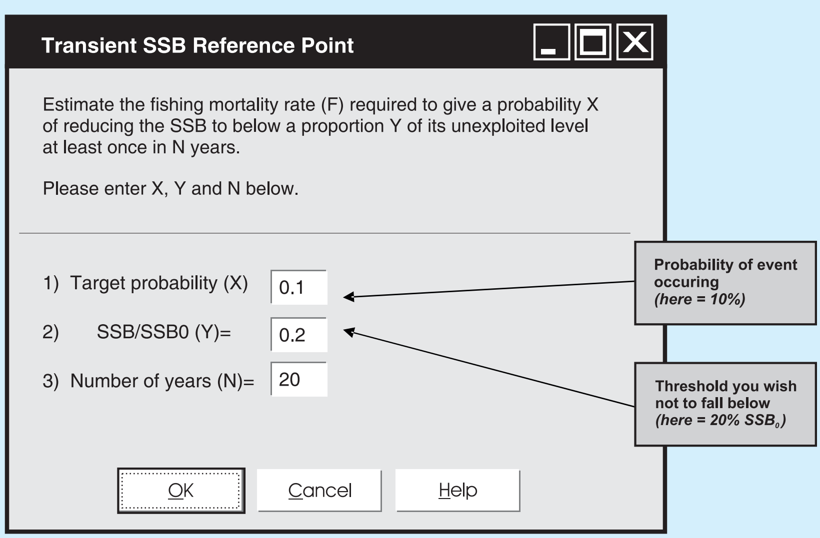
Having estimated the uncertainty and considered the risks, your managers need to work them into the management measures and the decision control rules. This can be done in a formal way as in the example shown in Figure 4. Uncertainty can also be allowed for in management without using such sophisticated rules. As shown in Box 21, risks can also be reduced just by adopting a more cautious reference point. You need to help managers to understand the uncertainties in the stock assessments and take appropriate actions. The degree of uncertainty in the assessment can often be reduced by better sampling (or a better sample design). But how much risk is acceptable must still be chosen by the fishery manager and stakeholders.

The fishery managers and other stakeholders need to decide how much risk is acceptable and take appropriate actions

e.g.

Box 19. Specifying risks with the Transient SSB reference point in Yield

In Yield, the transient SSB reference point gives the fishing mortality rate, *F*, associated with a specified probability that the spawning stock biomass (SSB) will fall below a selected threshold (e.g. 20% of the unexploited level) over a defined projection period. Using the 'Transient' routine as shown below, the value of *F* could be estimated with a range of different risks (e.g. a 10%, 20% or 30% chance that %SSB might fall below 20%; or a 10% chance that %SSB will fall below either 20% or 30%). Which of these levels of risk is acceptable should be decided by the managers.



e.g.

Box 20. Using confidence intervals to give advice on risks

If you estimate a 50% confidence interval for a forward projection of stock biomass in CEDA (see FTP 487, Figure 8.3), it could be interpreted that there would be a 25% risk that the estimated future biomass would be below the estimated lower confidence interval. In the Yield analysis in Figure 5, if managers were prepared to accept a 20% risk of the true F_{MSY} being lower than the one adopted, they could take the 20^{th} percentile estimate of F_{MSY} in the top left graph. If 100 simulations have been made (as in Figure 5), this could be found by exporting the data to a spreadsheet, sorting by size, and taking the 20^{th} lowest estimate of *F* as the adopted value. This approach allows for confidence intervals which are non-symmetrical, as frequently occurs for some variables (see e.g. FTP 487, Figure 4.7).

e.g.

Box 21. Allowing for risks by using more cautious reference points or decision control rules

If detailed risk assessments are not available, managers should adopt some other approach for allowing for uncertainty and risks. You could for example recommend using the *ad hoc* 2/3MSY as a limit reference point instead of the actual MSY. In designing decision control frameworks, you need to ensure that the managers fully understand the difference in risk between alternative reference points (such as in Table 4). Adopting $F_{20\%SPR}$ as a limit reference point is thus a higher risk strategy than choosing $F_{30\%SPR}$. Where the former is adopted, managers may reduce the risk of a stock collapse by also adopting a decision control rule with a larger precautionary adjustment in the threshold F_{pa} (e.g. adopting the 20^{th} percentile estimate from Yield instead of the 30^{th} percentile – see Figure 4).

6 References

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Annexes

Annex 1 below provides a checklist for you to ensure that you have provided the necessary advice to managers, allowing flexibility for the specific conditions in your fishery.

Annex 2 provides a glossary of terms used in these guides.

Annexes 3 and 4 illustrate possible uses of the FMSP tools in the commonly used ‘analytical’ and ‘biomass dynamic’ approaches to stock assessment.

Annex 5 describes the further benefits of using the ParFish tool in a co-management situation, or where limited data are available.

Annex 1. A checklist for fisheries scientists

What is appropriate for fisheries scientists to do in their stock assessments will vary considerably, according to a range of factors specific to your local situation. These will include:

- The nature of the fishery (for example, the scale and complexity, both of the fish stock and the fishing fleets and gears);
- The objectives of the fishery;
- The capacity of the management agency for data collection, assessment, monitoring and enforcement.

Recognising this need for flexibility, this guide has not given a fixed ‘to do’ list, as this would not be appropriate. The following checklist, however, suggests a number of points which you should consider somehow, at a level appropriate for your fishery, when providing stock assessment advice.

Phases 1 - 3: Preparing and developing the plan — **Tick boxes below**

Have you given your managers advice on the following?

- Identifying the appropriate unit stock for management? . . . . ☐
- The current situation of the fishery (status, pressures and threats): . . . . ☐
  - either from simple information on trends in catches and effort; or
  - using stock assessments?
- Suggestions for appropriate indicators and reference points (target/limit/ precautionary) for each objective proposed by the manager: . . . . ☐
  - using simple or arbitrary indicators and reference points where data are limited; or
  - using indicators and reference points that would require stock assessments to estimate them?
- How alternative management measures might best be used to achieve the proposed objectives, including what might happen under different scenarios? . . . . ☐
  - e.g. using simpler, rigorously determined and enforced, technical measures, such as closed seasons or areas, and/or size limit controls, where you have only limited information; or
  - input (fishing effort) or output (catch) controls where you have sufficient data and capacity to conduct stock assessments to advise what is appropriate.
- Setting the decision control rules? . . . . ☐

Have you considered the risk of stock collapse? . . . . ☐

- By conducting forward projections of stock size, with confidence intervals; or
- by using risk-based reference points?

Have you considered uncertainty? . . . . ☐

- Either by using more cautious reference points or decision control rules, where detailed risk assessments are not possible (eg, using 2/3 MSY instead of MSY); or
- by using risk-based reference points (for example, the transient SSB reference point in Yield)?

Have you conducted sensitivity analyses? . . . . ☐

- Where you may not be sure about particular data points or the reliability of particular data sources; or
- for testing the sensitivity of your results to using alternative models

Phase 4: Implementing and monitoring the plan

In conducting stock assessments, have you considered:

- What indicators and reference points you need to provide estimates of? . . ☐
- What data you have available? . . . . ☐
- What stock assessment tools you could use, depending on the chosen indicators and reference points, and the data and resources you have available, e.g.: . . . . ☐
  - biomass dynamic models, if you have a good time series of catch and effort data;
  - analytical models, if you have estimates of population dynamics parameters;
  - other methods, such as ParFish and the Beverton & Holt invariants, if you have very limited data.
- Which tool or tools would be most appropriate to use (where you have the resources and data to use alternatives)? . . . . ☐
- What additional data it would be appropriate (i.e., useful, feasible and cost- effective) to collect, in order to improve future assessments? . . . ☐

Have you presented your assessments to managers in a clear format?

- Including considering risk and uncertainty, and sensitivity analyses? . . . ☐
- Including details of the models and data used, and assumptions made? . . ☐

Annex 2. Glossary of terms

For management-related terms not included in this glossary, see also the glossary in the Managers Guide, or the FAO web site glossary (http://www.fao.org/fi/glossary/default.asp). For definitions of mathematical symbols, see FTP 487.

Analytical models	Stock assessment models that include a series of steps or processes in the relationships between fish biology and production, and between fishing activity and capture. Also known as dynamic pool models; may be either age-based or length-based (see Table 7).
Bayesian approach	A way of fitting models and making decisions that can combine different sources of information and can integrate the various uncertainties in an analysis (see Box 28).
Beverton and Holt 'invariant' method	A simple analytical stock assessment model, assuming standard 'invariant' dynamics within the fish stock, including a mortality / growth ratio of 1.5, and a length at maturity / maximum length ratio of 0.67 (see FTP 487, Chapter 11).
Biomass dynamic models	Stock assessment models that do not include the detailed intermediate processes of the analytical models, but assume a basic relationship between the biomass of the fish stock and its potential to produce catches. Provide the basis of MSY reference points.
Carrying Capacity	Represents the point of balance between reproduction potential and environmental resistance that is the maximum population of a species that a specific ecosystem can support indefinitely without deterioration of the character and quality of the resource. According to the MSY model, an exploited population reduced in size from its initial carrying capacity will tend to rebuild back towards this level.
CEDA	FMSP software for Catch Effort Data Analysis, including deterministic production models (e.g. Schaefer/logistic) and depletion models.
Decision control rules	A set of rules, agreed with stakeholders in advance, that govern the management of a fishery, e.g. by defined adjustments to management measures in response to observed annual levels of fishery indicators relative to the reference points. Recognising the trade-offs between goals, decision control rules define the priorities that are given to different objectives.
Decision tables	Used to present stock assessment results in a way that emphasises both the implications of alternative management options for each of the priority indicators (e.g. biological, economic, social, etc) and also the uncertainties in the analysis (e.g. by including confidence intervals and/or presenting results for different assumptions or models). See example in Box 14.

Depletion models	A general approach to estimating the size of a fish stock according to the ‘depletion’ in catch rates observed during a period when fish are being removed from the stock, either by a series of standard hauls (e.g. in a small enclosed lake), or by the commercial fishery. May be fitted by CEDA and/or used as inputs in ParFish.
Empirical models	Models based simply on experience, without making any assumptions on underlying analytical processes. Often constructed from data sets of measurements of independent and dependent variables, collected for a set of comparable fisheries or sites. May be used to find the average of some variable of interest (e.g. the catch per unit area), or to assess the relationships between variables and the effects of different management options (see FTP 487, Chapter 14).
FiSAT	A suite of stock assessment tools jointly published by FAO and ICLARM (download from http://www.fao.org/fi/statist/fisoft/fisat/index.htm).
Fishing mortality rate, *F*	An ‘instantaneous’ indicator of the proportion of the fishable stock that is caught within a given time period (see Box 1). Used as an indicator of the level of fishing pressure being applied to the fish stock, F forms the basis of many technical reference points, e.g. F_{MSY}.
FMSP	Fisheries Management Science Programme, of the UK Department for International Development (DFID). See www.fmsp.org.uk.
Growth overfishing	A situation when many small fish are being harvested, and the yield-per-recruit obtained from the stock is less than the maximum possible. Usually due to a combination of a high fishing rate and poor selectivity (e.g. small mesh sizes). Catching fewer small fish would lead to an increase in yield from the fishery. Growth overfishing does not threathen the long term sustainability of the fishery (unlike the more dangerous *recruitment overfishing*), but is an inefficient use of the stock.
Indicator	A specific state, or variable, which can be monitored in a system (e.g. a fishery) to give a measure of the state of the system at any given time. In fisheries management, each indicator would be linked to one or more reference points and used to track the state of the fishery in relation to those reference points.
Intermediate parameters	Parameters estimated by or used in stock assessment models that are involved as intermediate steps in the assessment process but are neither indicators nor reference points (e.g. the von Bertalanffy growth parameters).
LFDA	FMSP software for Length Frequency Distribution Analysis, used to estimate growth parameters and the total mortality rate, Z.

Limit reference point	A reference point used as a limit in a decision control rule framework is a point that it would be dangerous or undesirable to go beyond. It may either be an upper limit (e.g. in the case of fishing mortality rates) or a lower limit (e.g. in the case of a minimum viable spawning stock biomass). Commonly used in combination with *precautionary reference points* to avoid being exceeded. *Cf. target reference point.*
Management measures	Specific controls applied in the fishery to contribute to achieving the objectives, including some or all of the technical measures (gear regulations, closed areas and/or closed seasons), input controls (on fishing effort), output controls (on catches), and any access rights designed around the input and output controls.
Management strategy	The strategy adopted by the management authority to achieve the objectives, comprising the full set of management measures applied in that fishery.
Management standards	A 'catch-all' term for the elements of the management system that are *quantified*, either fully or partially (including the detailed objectives, and estimates of indicators and reference points), that guide management, and enable stakeholders to judge its effectiveness.
Mortality rates (see also fishing mortality rate)	The rate at which the numbers in a population decrease with time due to various causes. To facilitate calculations, scientists express mortality as an exponential or 'instantaneous' rate, where $N_t/N_0 = e^{-Zt} = e^{-(M+F)t}$ in which N_t/N_0 is the survival rate; *M* is the natural mortality rate (of deaths due to predation or disease); *F* is the fishing mortality rate (deaths due to fishing); *Z* is the combined total mortality rate; and t is time.
Objectives	Statements that define, quantify and prioritise the fishery objectives, in terms of four key elements: 'verb' – 'objective' – 'relation to' – 'reference point'. Such statements should quantify the hierarchy of objectives and resolve any trade-offs between them. Referred to as 'operational objectives' in some texts (e.g. Cochrane, 2002), reflecting their key role in re-expressing the goals in practical, compatible terms.
ParFish	FMSP software for Participatory Fisheries stock assessment and management, especially useful in data-limited situations and for supporting co-management approaches.
'Per recruit' indicators and reference points (e.g. YPR, BPR, $F_{\%SPR}$)	As estimated by 'analytical' SA models, showing the average yield or biomass expected from each single fish that 'recruits' to the fishery. Useful in situations where the actual number of ecruits each year is not known, i.e., where no 'stock-recruit relationship' (SRR) has been fitted. Note that ignoring the existence of a SRR may risk 'recruitment overfishing'. See also Box 24 in Annex 3.

Precautionary approach	One that recognises the many uncertainties relating to the our knowledge of the system (e.g. the natural productivity of the stocks, the true values of reference points, the current size of the stock and the effect of future management actions), and adjusts management actions accordingly.
Precautionary reference point	Reference points used as thresholds for action to avoid the risk of going beyond limit reference points, at which irreversible damage may be done to the stock. They should be set at levels which reflect both the degree of uncertainty in the assessment, and the level of risk tolerance of the managers and/or other stakeholders.
Production Model	A model describing the relationship between fish production (and potential catch), the size of the fish stock, and the level of fishing effort (see e.g. Figure 2). Commonly used to refer to the 'surplus production' or biomass dynamic models available in CEDA, such as the Schaefer and Fox forms. But may also cover those analytical fishery models which include a stock recruit relationship (and which will predict a stock collapse at high fishing effort).
Projection	Estimation of the future stock sizes (or other selected fishery indicators) starting from the current time. Projections are usually made for different levels of management measures and show for example how long the fishery may take to 'recover' in each case to the level of a given reference point (e.g. B_{MSY}, the biomass that would give MSY).
Recruitment overfishing	Fish are defined as recruits when they grow large enough to be caught by the gears in use, and/or migrate from unfished juvenile/ nursery grounds into the waters fished by the fishing fleets. Recruitment overfishing is when the stock size is reduced below a level at which the number of new recruits produced each year is significantly reduced below normal. At this point, the stock may go into a dangerous downward spiral and eventually collapse. Cf. *growth overfishing*.
Reference point	A specific value of an indicator, used as a guide in fishery management (see also *technical, target, limit* and *precautionary reference points*)
Risk	The chance or probability of something bad happening, e.g. expressed as the expected frequency of its occurrence over a stated number of years.
Scenario	A defined set of management measures (and model assumptions) that may be assessed or compared with other scenarios in a stock assessment. Examples – 1: reduce fishing effort by 25%; 2: reduce fishing effort by 50%; 3: introduce a 3 month closed season from June-August (on its own or combined with 1 or 2); etc.

Sensitivity analysis	The testing of alternative but feasible data sets, parameter values or model assumptions (or 'states of nature') to determine their implications for the results of a stock assessment. Often presented in the form of a decision table, showing which uncertainties have the largest influence on the results.
SPR / SSBPR	Spawning products per recruit / spawning stock biomass per recruit. Indicators of the relative spawning potential of an average individual fish (recruit), that vary depending on the fishing mortality rate operating in the stock. Often expressed as a percentage of the level that would exist in an unfished stock, e.g. as in $F_{\%SPR}$ or $F_{\%SSBPR}$.
Stock assessment (SA)	The process of collecting and analysing biological and statistical information to determine the changes in the abundance of fishery stocks in response to fishing, and, to the extent possible, to predict future trends of stock abundance depending on alternative management options.
Stock assessment (SA) tools	Mathematical fishery models, software packages, or sets of guidelines that assist scientists to assess the state of a fish stock and the likely implications of alternative management actions.
Strategic stock assessments	Estimate both indicators and reference points, and may also use long-term projections and risk assessments, and thereby assist managers to choose between different management measures or levels of controls. Note that a full 'management procedure evaluation' (as described in Section 3.6.5 of FTP 487) is an even more complete assessment of the overall system, including data collection and enforcement.
Tactical stock assessments	Provide short term 'operational' or 'tactical' advice to managers on the current state of the fishery system, as measured by the selected indicators, and any adjustments required to the management measures (usually input or output controls) to achieve the objectives.
Target reference point	A reference point used as a target in a decision control rule framework is a point to aim at. Actual values of the indicator slightly above or below the target are both acceptable. *Cf. Limit reference point.*
Technical reference points	Estimated values derived from agreed scientific procedures and/or models corresponding to a defined state of the resource and/or of the fishery, and used as a guide for fisheries management. Some reference points are general and applicable to many fish stocks (e.g. the MSY catch or the $F_{0.1}$ fishing mortality rate), others could be stock-specific (e.g. an average catch per unit effort of X tonnes, taken by vessel type Y using standard gear type Z). Some reference points explicitly specify the risks of defined undesirable events occurring.

Uncertainty	The incompleteness of knowledge about the state or process of nature: including the true values of reference points and other population parameters, and the relative importance of internal and external influences on the fishery resource.
Unit stock	A group of individuals in a species occupying a well defined spatial range, independent of any other stocks of the same species, that can be regarded as a single 'unit' for management or assessment purposes.
Virtual Population Analysis (VPA)	A family of models (including 'cohort analysis') used to estimate the fishing mortality rate, *F*, and the numbers of fish recruiting to the fish stock each year (see Box 12). Requires input time series data on the total catch in each age group in each year.
von Bertalanffy growth function (VBGF)	An equation describing the growth of fish over time, often used in analytical fishery models. It assumes that fish grow at a rate K, towards an asymptotic length L_∞, according to the equation: $l_t = L_\infty(1 - e^{-K(t-t_0)})$, where *t* = time. The parameter t_0 is the theoretical age at which the fish would have had zero length if growth had followed the VBGF from birth.
'Yield'	FMSP software, using an age-based, analytical model, for estimating yield and biomass-based indicators and reference points (both *per recruit* and *absolute*), allowing for uncertainties in parameter inputs.

Annex 3. The analytical approach to stock assessment using LFDA and Yield

The analytical or dynamic pool approach models the numbers, maturity and size of fish in each age and/or length class

The analytical approach to stock assessment is where a number of intermediate processes are modelled describing the dynamics of the fish stock and the effect of fishing. As illustrated in **Figure 6**, this approach can be applied using the FMSP tools LFDA and Yield. In this case, LFDA is used first to estimate the *intermediate parameters* describing fish growth, and second to estimate the fishing mortality rate, F_{eq}, as an *indicator* of the current fishing pressure. The growth parameters from LFDA are then used in the FMSP Yield software along with various other inputs to estimate a range of alternative *F*-based *reference points* for comparison with F_{eq}. Strategic management advice is provided by Yield on the likely effect of different management options on alternative yield and biomass indicators (e.g. relative to the reference points). Having selected the management measures, tactical management advice may be provided by comparing the relative values of the F_{eq} indicators from LFDA and the *F*-based reference points from Yield.

Box 22. Do I have to use LFDA and Yield together?

Yes and No. Although LFDA and Yield are two separate software packages, their joint use is presented here as one overall stock assessment ‘approach’. This is to emphasise that using either LFDA or Yield on their own will not allow a full stock assessment. LFDA provides estimates of intermediate parameters (growth rates) and indicators (F_{eq}); Yield provides estimates of reference points. Both indicators and reference points are needed to provide guidance to managers.

While you need to cover both parts of the process, and you can use LFDA and Yield together as illustrated here, you could also use other tools to substitute each part of the process. If, for example, you already have estimates of all the necessary intermediate parameters, you could go directly to Yield to estimate your reference points and uncertainty. Or if your fish species can be aged by reading otoliths, you could estimate the growth and mortality rates using a spreadsheet instead of LFDA, and then go to Yield. Or if you wish to estimate bio-economic reference points, you could use LFDA first, then use the intermediate parameters in your own spreadsheet.

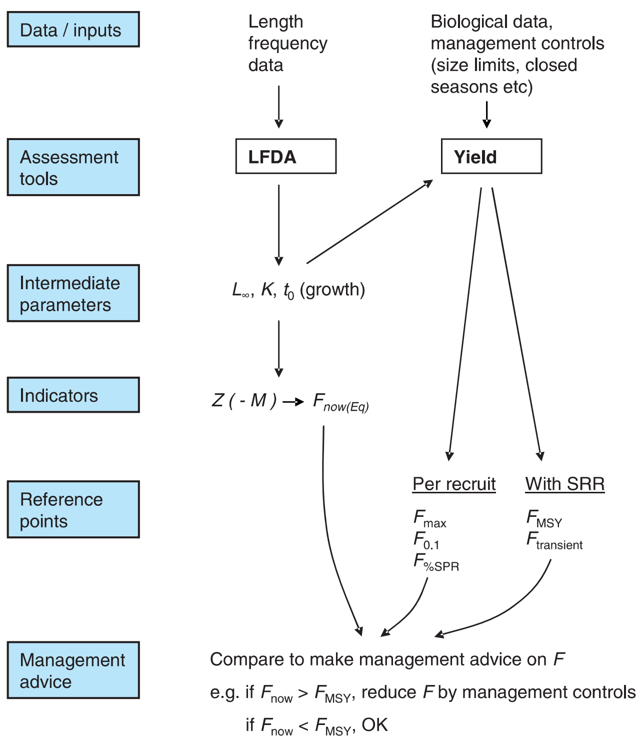

Figure 6. Information flows in the analytical or dynamic pool approach to fish stock assessment, using the FMSP LFDA and Yield software tools

Estimating growth and mortality rates using LFDA or other methods

The LFDA package provides a variety of methods for estimating growth parameters and mortality rates from fish length frequency distributions. The LFDA software requires a *time series* of length frequency samples, e.g. collected every other month, for a full year. For species with moderate or fast growth and with reasonably non-selective sampling, such length frequencies should show a seasonal progression of modes as fish grow through the length classes. LFDA attempts to find the best fitting growth curve through the length frequency data, as illustrated in Figure 7. Having estimated the growth curve, three different methods may be used to estimate the total mortality rate, Z. Each of these methods is broadly based on the relative numbers in the different age classes identified in the stock. The average *fishing* mortality rate over recent years, F_{eq}, is

LFDA attempts to find the best fitting growth curve through a set of length frequency data – it can then estimate the mortality rate as an indicator of fishing pressure estimated as the indicator of fishing pressure by subtracting the estimated natural mortality rate, *M* from *Z* (since *Z* = *F*+*M*). *M* is often not well known, but can be estimated from the growth parameters e.g. using the ‘Pauly’ option in Yield (see FTP 487, Section 3.3.3). M, estimated in this way will usually have wide confidence intervals and the importance of that uncertainty in *M* can be tested in the stock assessment using sensitivity tests.

Box 23. Which of the different LFDA fitting methods should I use?

The relative performance of LFDA’s alternative fitting methods varies with the growth and mortality patterns of different fish stocks. Users are advised to try each of the methods on their data, and then judge which method appears to provide the best fit (see FTP 487, Sections 3.1.5 and 6.1). Where a range of growth rates fit equally well, the different mortality estimators should usually be attempted for each feasible combination of growth parameters. This will show you roughly the uncertainty in your parameter estimates.

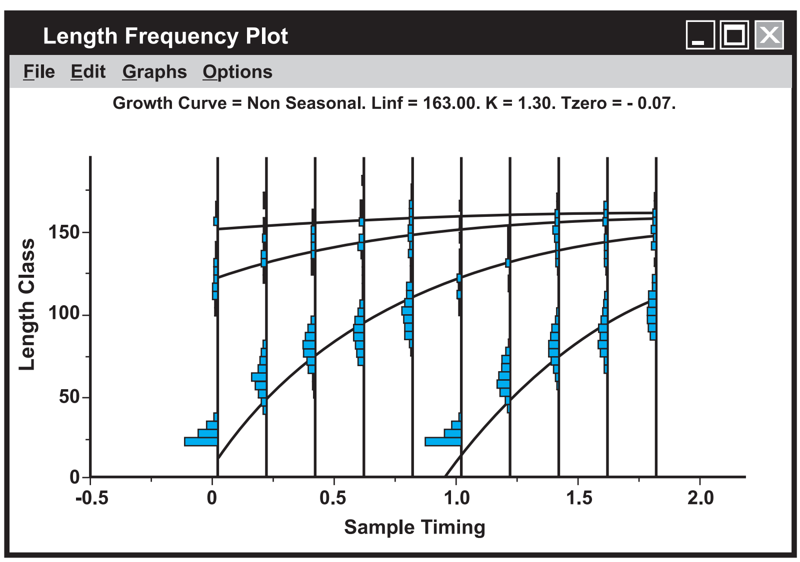

Figure 7. Illustration of LFDA fitting of the von Bertalanffy growth curve through a simulated set of length frequency data, with five samples taken each year over a two year period. In this example, the new recruits first appear in the fishery at the start of each year (at sample times ‘0’ and ‘1.0’). They then grow to a length of around 100 length units by the end of their first year. Some two and three year old fish are still visible in the samples with the curve also passing through those modes. Due to variation in the growth of individual fish, and the slowing down of growth with age, the modes for older fish usually merge together. Length-based methods thus work best with non-selective gears that sample both small and large fish equally well.

How does the Yield analytical model calculate fishery indicators?

Yield estimates indicators and reference points for both stock biomass and catches

The 'Yield' software uses a standard age-structured population dynamics model to estimate yield and biomass-based indicators and reference points allowing for uncertainty in parameter inputs. While LFDA estimates the current value of the indicator of fishing *pressure*, F_{eq}, Yield predicts the likely effect of this or alternative fishing pressures (and alternative closed seasons or size limits), on indicators of the fishery *state*. Yield thus predicts both the yield to the fishery and the biomass of the fish stock that might occur at different levels of F and with different closed seasons and size limits. From this information, Yield estimates reference points, such as $F_{0.1}$ or $F_{20\%SSB}$, corresponding to defined values of the yield and biomass indicators.

The underlying model in Yield (and other analytical approaches) is illustrated in Figure 8 and Figure 9. Figure 8 shows some of the key population dynamic processes in an *unexploited* fish stock. In Figure 8A, individual fish are shown to grow according to the assumed von Bertalanffy growth curve, increasing in length with age at a rate K, up to the asymptotic length, L_{∞}. In Figure 8B, the weight at age of individual fish is estimated from their lengths according to the relationship $W = a\,L^{b}$. The numbers of fish decline with age according to the exponential mortality model, at a rate determined by the natural mortality rate, M (Figure 8C). The total biomass at age is then simply found by multiplying the individual weights at age by the numbers at age (Figure 8D). This increases up to a maximum at some middle age and then declines to zero as all the fish in the age class eventually die off. The actual age at which the peak biomass occurs depends on the relative rates of growth and mortality. The mature biomass or spawning stock biomass at age (SSB in Figure 8F) is the total biomass times the proportion at each age which has already reached maturity (Figure 8E).

Analytical models show the importance of keeping enough mature fish to ensure next year's recruitment to the stock

Assuming constant (equilibrium) conditions in the stock, the total spawning stock biomass in an unexploited stock can be represented as the sum of all the biomasses at age, i.e., the shaded area under the curve in Figure 8F. Analytical models recognise the importance of maintaining enough of this mature biomass to ensure future recruitment to the fish stock.

For an *exploited* fish stock, analytical models investigate the additional effect of fishing on the stock biomass and the yield. The underlying processes of growth in length and weight (Figure 9A, B) and of fish maturation (Figure 9E) are often assumed to be the same in an exploited stock as in an unexploited one (in fact there may be some small density dependent response but this is ignored in Yield). In contrast, the numbers at age and the biomass at age will clearly decline more rapidly in an exploited stock due to the extra effect of fishing mortality (compare Figure 9C and Figure 9D with Figure 8C and Figure 8D respectively). The spawning stock biomass in the fished stock (Figure 9F) will also be lower than in the unfished stock (Figure 8F). The catch in the fished stock (the shaded area in Figure 9H) depends on the total biomass at age and the fishing mortality rate at age (Figure 9G). The latter depends on both the overall intensity of fishing (i.e. *F*) and the selectivity of the fishing gear(s) in use - Figure 9G assumes that fishing mortality rate increases gradually as fish become vulnerable to the mesh sizes in use, and is then constant (at 100% of *F*) for most larger (older) sizes of fish.

'Analytical' models such as Yield thus estimate indicators of both fish catch and biomass (total and mature) by calculating a series of intermediate steps representing the real processes in the fish stock and in the capture of fish. The relative values of these indicators vary with the fishing mortality rate and selectivity and timing of the fishery. Strategic fishery assessments report the relative sizes of the shaded areas in Figure 9F and Figure 9H for alternative management scenarios (e.g. different levels of *F*, closed seasons, size limits etc).

Estimating reference points in Yield

The graph on the right of Figure 9 illustrates the process by which *F*-based reference points are found from the different yield and biomass indicators. Yield simulates each of the analytical processes to estimate the values of each yield and biomass indicator for a range of different values of *F*. The $F_{20\%SPR}$ reference point is then found from the biomass-*F* curve as the level of fishing mortality at which the spawning stock biomass per recruit (SSBPR in Yield) is reduced to 20% of the level in the unfished stock. The $F_{0.1}$ reference point is found from the yield-*F* curve at the point where the slope of the curve is 10% of that at the origin.

If you can only estimate 'per recruit' reference points you should avoid recruitment overfishing by setting a limit reference point based on the spawning stock biomass per recruit

Yield allows you to estimate both 'per recruit' and absolute indicators and reference points (see Box 24). Where stock recruitment data are not available and only per-recruit models are possible, as will often be the case, the first priority should be given to setting *limit* reference points based on spawning stock *biomass* per recruit. As shown in Figure 3.1 in FTP 487, the *F* levels associated with critical reductions in spawning stock biomass (e.g. to the $F_{20\%SSB}$ reference points) are similar whether or not a SRR is included, so the simpler per-recruit assessment can still provide relatively safe advice. Target reference points may also be estimated based on *yield* per recruit, but these should take a lower precedence than the *SSB*-based LRPs.

Box 24. 'Per recruit' models, growth overfishing and recruitment overfishing

Simple analytical models assume that fish recruitment is constant, and estimate the numbers and biomass on a relative basis or 'per recruit'. This makes the assessment much easier as data on the relationship between stock size and the resulting level of recruitment are often the most difficult to obtain (e.g. using 'VPA' methods). 'Yield per recruit' or YPR models thus look simply at the trade offs between the loss in biomass due to mortality and the gains in biomass due to the growth of individual fish. Given the balance of these parameters, certain values of *F* and age at first capture will give the maximal yield (per recruit) from the fishery. Catching too many fish at an age less than this will lead to 'growth overfishing' in the stock.

In practice of course, the level of annual recruitment clearly must be related to the size of the stock. If the stock gets *too* small, the level of recruitment (the numbers of new fish being spawned and entering the fishery each year) must decline. Including a stock recruitment relationship (SRR) in an analytical YPR model changes its predictions dramatically. While YPR often rises asymptotically with increasing *F*, a Yield model with a SRR operates more like a 'biomass dynamic' or 'surplus yield' model in that yield will decline when *F* gets too high, and will eventually reach a point of stock collapse (see Section 3.1.6 and Figure 3.1 in FTP 487). Including a SRR in Yield enables investigation of 'recruitment overfishing' and the estimation of reference points related to both the yield and the protection of the spawning stock.

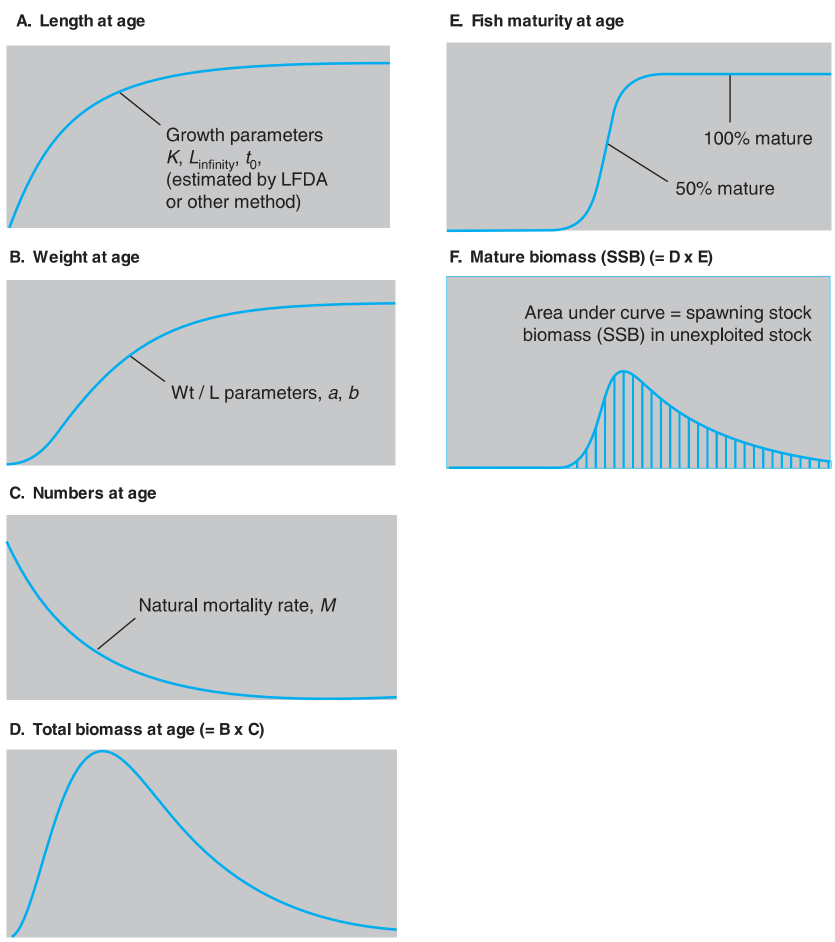

Figure 8. Steps in the 'analytical' fishery model used in Yield, illustrating the estimation of the spawning stock biomass (SSB) for an unexploited fish stock

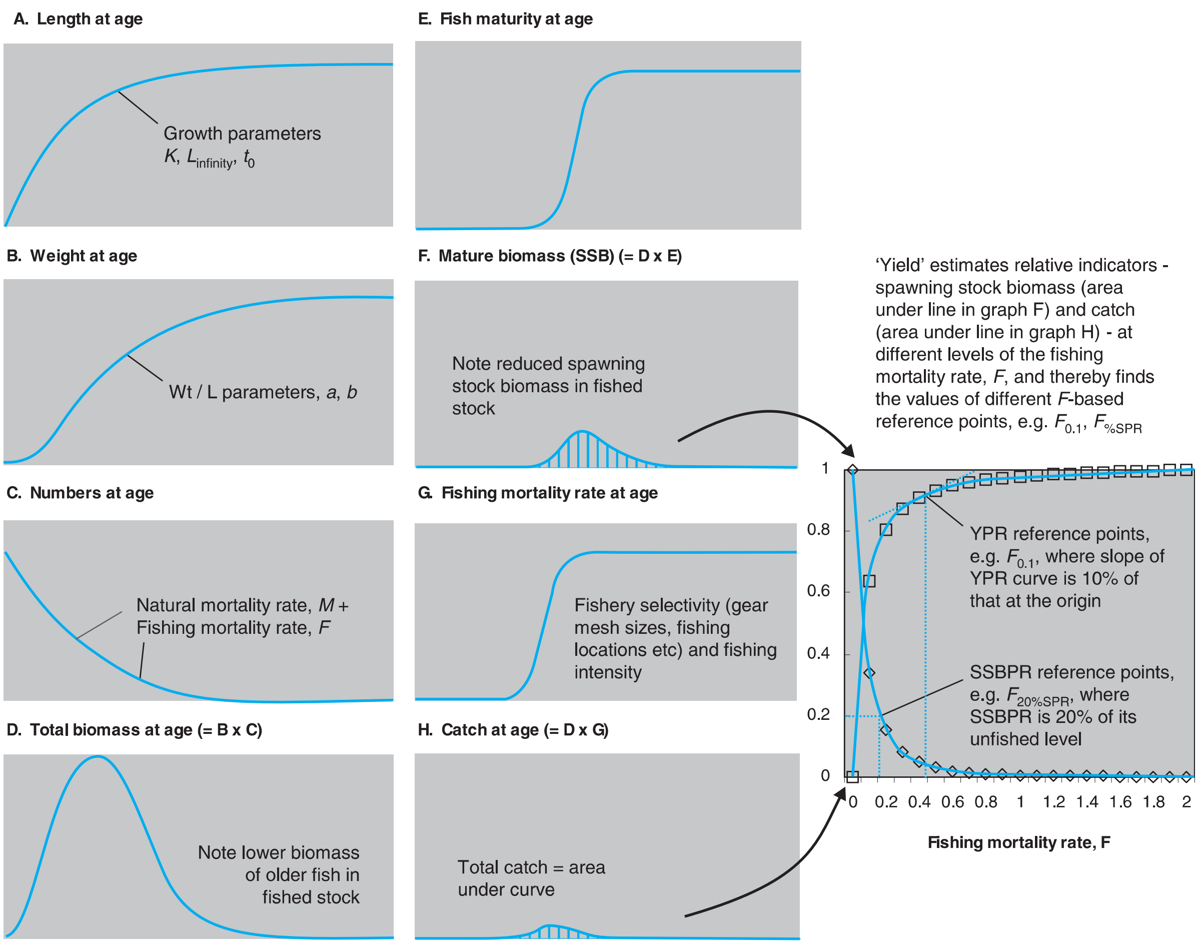

Figure 9. Steps in the Yield 'analytical' model for an exploited fish stock illustrating the estimation of spawning stock biomass per recruit (SSBPR) and yield per recruit (YPR) indicators in graphs F and H, and related fishing mortality (F)-based reference points

Allowing for uncertainty and providing advice to managers

If there were no statistical uncertainty about any of the biological and fishery parameters, then there would be just a single certain value of each indicator for each value of *F*. In reality there is always some degree of uncertainty about the input parameters, and there will always be corresponding uncertainty about the indicators and hence the reference points.

Yield shows the uncertainty in the model outputs by repeating the analysis many times with different inputs each time

The Yield software enables the importance of this parameter uncertainty to be assessed. Uncertainty may be input for one or more of the input parameters by entering the coefficients of variation of the parameters and defining the distributions as either normal, logarithmic or uniform (see help files). Yield then selects a large number of sets of biological and fishery parameters by sampling from the defined probability distributions (i.e. 'Monte Carlo' sampling). The quantities of interest are then calculated for each set, giving distributions of outputs. For the YPR and other indicators estimated by Yield, graphs are presented with confidence intervals (see FTP 487, Figure 4.2). For the reference points, frequency distributions are graphed showing the range of answers achieved in each run of the model (see Figure 5). In each case, the actual result found in each simulation may be accessed in a table of results.

You can use the outputs from Yield to estimate precautionary reference points with defined levels of risk

As a 'central' value of the indicators or reference points, either the average or median values may be used. These are easily calculated from the tables of results that accompany the results graphs (e.g. by exporting to a spreadsheet). The same tables of results may also be used to estimate precautionary values of the *F* reference points, e.g. as the 5%, 10% or 20% lower percentiles, depending on the risk tolerance defined by the managers.

Most of the reference points estimated by Yield are 'equilibrium' analyses assuming constant recruitment to the stock. The 'Transient' option described in Section 5.5 allows for uncertainty in both the parameter values and in the inter-annual variability in recruitment strength. As shown in the example analysis below, including this additional uncertainty usually reduces the reference levels for fishing mortality.

Box 25. Example analysis using the analytical approach with LFDA / Yield

The Yield software help file includes a detailed example analysis using data for *Lethrinus mahsena*, one of the main species taken in fisheries for snappers and emperors in the western central Indian Ocean. In that example, growth parameters were estimated using both LFDA and age-based methods for several different fishing locations in the Indian ocean. The uncertainty in the growth rates was estimated as the coefficient of variation among the 12 different sets of estimates obtained. Uncertainties were also entered for some other parameter inputs, but not all.

Several *F*-based reference points were then calculated as listed below:

Reference Point	2.5 %ile	Median	97.5 %ile
Equilibrium $F_{0.1}$	0.31	0.40	0.54
Equilibrium $F_{20\%\ SSB\text{-}per\text{-}recruit}$	0.31	0.45	0.70
Equilibrium F_{MSY}	0.27	0.41	0.70
Equilibrium $F_{20\%\ SSB}$	0.25	0.37	0.54
Transient $F_{20\%\ SSB}$		0.26	

As median values, all of the above equilibrium reference point *F*s are similar and approximately equal to the mean value of *M* (0.39). This is quite often the case. The F_{max} reference point was far above these values (median around $F = 2$), confirming the likely unreliability of YPR as an indicator where recruitment data are ignored. The transient SSB reference point was somewhat lower than even the lower 2.5 percentiles of the equilibrium reference points (percentiles are not calculated by Yield for the transient reference point due to the long time required for the simulations). On the basis of these results, precautionary or limit reference points for the fishing mortality rate could be selected in the range 0.25 – 0.35 depending on the priority objectives and the risk tolerance adopted by the managers.

The remote Chagos Archipelago fishery for *L. mahsena* is believed to be relatively lightly exploited, with an *F* around 0.2. Comparing this to the reference points, the analysis suggests that an increase in *F* of up to 50% may lead to a sustainable increase in catches. However, the primary concern of the current management regime for the Chagos Archipelago is to ensure stock conservation, rather than to maximise sustainable resource exploitation. On those grounds, the current regime appears to be performing well.

Annex 4. The biomass dynamic approach to stock assessment using CEDA

Biomass dynamic models ignore the age and size structure of the fish stock and provide advice on catch and effort levels, not technical measures

Biomass dynamic models provide a simple but powerful approach for carrying out a full fish stock assessment. As mentioned in Section 2.2, only data on total catch and an index of abundance (e.g. CPUE) are required. All aspects of production – recruitment, growth and mortality – are pooled into a single function related to the fish biomass. The age and size structure included in the analytical models are thus ignored, making these models relatively easy to use. The drawback is that no advice can be provided on technical measures (size limits, closed seasons, etc). The outputs also need to be treated with caution in any case where the selectivity of the fishery is changing, especially if fish are increasingly being targeted at sizes smaller than the size at maturity.

Biomass dynamic models and depletion models were described in some detail in Section 4.5 and Chapter 8 in FTP 487. The CEDA software includes options for fitting four different types of these models. This annex focuses on the variable recruitment ‘production models’, including the commonly used Schaefer, Fox and Pella-Tomlinson methods. Other CEDA model options are described in Section 4.5.1 of FTP 487.

CEDA fits four different models – this annex only looks at the Schaefer ‘production model’

Production models assume that recruitment or production is ‘deterministic’; that is, controlled entirely by current stock size, without any environmental effects or other sources of ‘random’ variation. The confidence intervals around r and K will give an indication of the total uncertainty, including that caused by such random variation. The Schaefer, Fox and Pella-Tomlinson models each have differently shaped functions, describing the relationship between current stock size and production. They all have in common the idea of a constant carrying capacity or unexploited population size, K, at which level the population would stabilize in the absence of exploitation. With this assumption, a population whose current size is below carrying capacity will tend to increase towards the carrying capacity, subject to any catches that are taken. If more catch is taken than the natural productivity at that biomass size, the stock size will decline.

What does a biomass dynamic stock assessment involve?

The flow of information through a CEDA biomass dynamic fishery assessment is illustrated in Figure 10. How the model actually works is illustrated in the example analysis in Figure 11. In this analysis (based on the CEDA software tuna tutorial data set), fishing effort increased steadily over the period of the data set (1934 to 1967) while fish catches only increased up to the late 1940s, and then levelled off after that. Reflecting these two trends, the fish *abundance* (as measured by the index CPUE) appeared to have declined gradually over the time period (as shown by the dotted line in Figure 11A).

CEDA estimates the parameters of the equilibrium relationships between stock biomass, fishing effort and the potential catch, from which we can estimate the MSY reference points

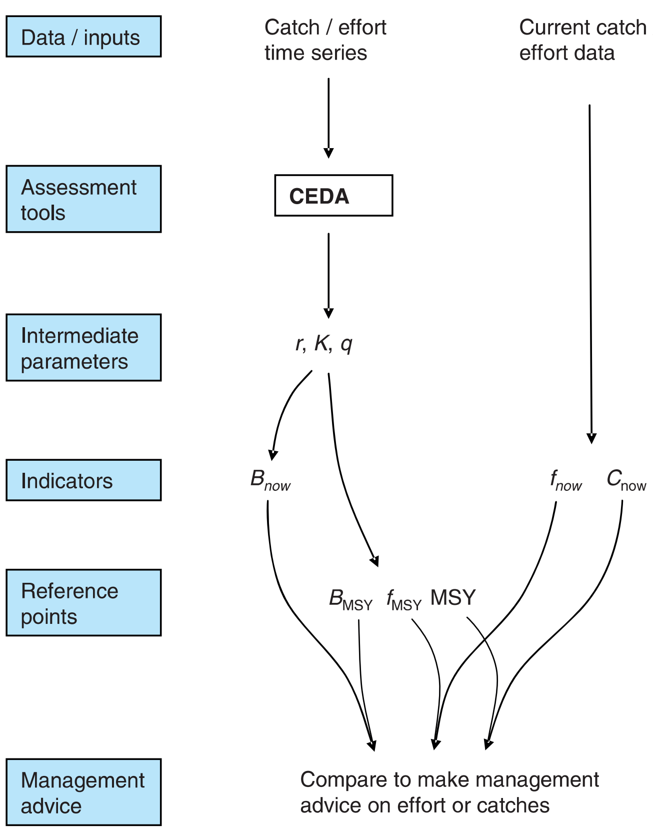

Figure 10. Information flows in the 'biomass dynamic' approach to stock assessment using the FMSP CEDA package

CEDA estimates the intermediate parameters, *r*, *K* and *q* of the biomass dynamic production models and the current biomass, B_{now}. The parameters define the equilibrium relationship between the biomass of the stock and the potential catch available on a sustainable basis as shown in Figure 11B. This provides reference points, such as the maximum sustainable yield, MSY (the peak of the yield curve), and the biomass, B_{MSY} at which it may be achieved.These can be compared directly with the current catch and the estimated B_{now} to see if they are likely to be sustainable. The fitted model can also be used to make projections of the likely future biomass at alternative levels of catches or fishing effort (see Figure 11C and Box 27 below).

Fitting the non-equilibrium biomass dynamic model

CEDA uses non-equilibrium fitting methods but still estimates the long-term equilibrium relationships between catch, effort and biomass

In CEDA, production models are fitted using non-equilibrium methods. This means that the data inputs are recognised to have come from a period when the stock was not at equilibrium. The fitted models and reference points nevertheless predict the relationship between catch and biomass (and between catch and effort) in an equilibrium situation.

Three different production models may be fitted (the Schaefer, Fox and Pella-Tomlinson forms), each with three alternative error models: normal, log normal or gamma. The CEDA software help files provide guidance on how to fit the models, including the use of diagnostic tools (residual plots, and goodness of fit measures) to find which model provides the best fit. As with Yield, sensitivity analyses are recommended to determine the effect of uncertainties in the model forms and parameters (see Section 5.4).

CEDA needs a 'good' index of abundance that is proportional to the actual stock size

Production models require time series inputs of both fish catches and an index of abundance. The best results are obtained where a comprehensive record of total catch is available with no gaps since the start of the fishery. If the catch data are incomplete, the unexploited population size, *K* will be underestimated, as will all subsequent population sizes. The abundance index data need not cover the whole period of the data set, and there may be gaps in the time series. A 'good' index of abundance must however be used, which means it should be proportional to the actual population size over a wide range of sizes. The two most common types of index are research survey data and commercial CPUE data. The CEDA help files discuss the pros and cons of each type of index. CPUE data can be easier to collect but can cause problems if the spatial distribution or catchability (capture efficiency) of the fleet has changed over time. Where helpful (e.g. for multi-fleet fisheries), CEDA can use 'partial' CPUE data derived only from that sub-set of boats which are thought to provide the best index of abundance, e.g. the fleet that has changed least over time and has fished mostly in the same areas for the full time series.

Box 26. What if I can't get any CEDA model to fit the data?

With some data sets, non-equilibrium biomass dynamic models will fail to provide any reasonable fit. This usually happens where few data are available or where the data are incompatible with the assumptions of the models, e.g. if the CPUE goes up instead of down even when the fishery shifts to a phase of taking higher total catches. This pattern may mean that the assumption of a constant carrying capacity has been violated, e.g. if another species has been fished out leaving more prey available to the stock. With some data sets, a model can be fitted but the confidence intervals may be so wide as to be almost meaningless. In these situations, it should be realized that one's information is inadequate for the production of useful advice. This is still preferable to an equilibrium fit which is frequently wrong. It is thus far better to recognize the limitations in the data, than to follow results blindly and provide bad advice. A precautionary manager would still limit the expansion of the fishery in this case, until better data were collected and more reliable management advice could be produced.

CEDA estimates the confidence intervals of the model parameters by bootstrapping (re-sampling from the residuals of the C/E data points and re-fitting the parameters for multiple runs of the model). Confidence intervals will often be asymmetrical for one or more of the parameters (see examples in FTP 487, Figure 4.7). Confidence intervals for the final stock size (at the end of the time series) are not reported with the other estimates of *K, r, q* etc, but can be found by making a projection 'with confidence intervals' and then clicking on the button to copy the graph source data to a spreadsheet.

Biomass dynamic models will sometimes fail to find any reasonable fit to the data, e.g. when you have too few data points, or the model assumptions are not valid

Providing advice to managers

These models tell managers the maximum sustainable yield (MSY) of the fishery and the level of fishing effort that would achieve it

Having estimated the intermediate parameters defining the equilibrium yield curve (e.g. as in Figure 11B), a range of useful reference points can be provided to managers. In the case of the logistic (Schaefer) model, the biomass associated with the MSY, B_{MSY} is found at $K/2$, and the MSY catch level is equal to $rK/4$. For data sets where the effort inputs relate to the total catches (not the 'partial' catches for a selected fleet), the effort giving the MSY, f_{MSY} is equal to $r/2q$ (and thus $F_{MSY} = r/2$). The maximum possible F (the point at which the stock collapses) is equal to r, and the effort at the maximum possible F will be r/q. Equivalent points for the Fox and Pella-Tomlinson models are given in the CEDA Technical Appendix help files.

With this information, it is easy to compare current estimates of fishing effort f_{now}, fishing mortality rate, F_{now} or catch with the equivalent reference points, f_{MSY}, F_{MSY} or MSY. Tactical management advice may be provided as the proportional adjustments to catches or effort required to bring the fishery to the equilibrium MSY state.

With its non-analytical approach, CEDA is mainly designed to assist fishery management based on fishing input (effort levels) or output controls (catch quotas or TACs). The effort related quantities f_{MSY} and F_{MSY} are best estimated for single fleet fisheries where catch and effort data relate to the whole fleet. Regardless of whether full or partial effort data are used, CEDA may always be used to provide estimates of C_{now}/B_{now} (a proxy for F_{now}) and C_{MSY}/B_{MSY} (a proxy for F_{MSY}). Where overall catchabilities are not known (i.e. for multi-fleet fisheries analysed with partial abundance estimates in CEDA), f_{MSY} may *not* be known, but simple forms of effort control may still be feasible, based on the relative proportions of F_{now} and F_{MSY}.

The estimated 'MSY' catch will only really be sustainable if the current stock size is above B_{MSY} – as may be checked using a CEDA projection

Catch or effort controls may either be set immediately at the levels estimated to deliver the MSY catches, or at levels predicted to rebuild to MSY in a selected number of years. CEDA projections thus show the expected effect of alternative control levels on the stock biomass, starting from the current stock size (i.e., at the end of the time series). As shown in Box 27, the MSY catch may not actually be sustainable if the current or final biomass is below the level B_{MSY} that would allow MSY to be taken. In accordance with the precautionary approach, it is also strongly recommended that MSY, f_{MSY} and B_{MSY} are treated as limit reference points rather than target reference points and the target catch and allowable effort are set at levels below the MSY levels, for example 10 or even 20% lower.

Box 27. Using CEDA projections to provide strategic management advice

The tuna tutorial in the CEDA software help file demonstrates the use of diagnostic tools to examine alternative production model fits allowing for uncertainty. With this data set, none of the alternative models provide very good fits due to the existence of both outliers and trends. The fit of a least-squares Schaefer model to these data was illustrated in FTP 487, Figure 4.6, and is further used here in the same example redrawn in Figure 11.

With this data set, the final biomass at the end of the time series, B_{1968} was estimated by the Schaefer model as 489 Kt, significantly below the B_{MSY} estimated as 653 Kt. Fishing between 1934 and 1967 was thus found to have reduced the stock size to less than half of the initial biomass (assumed equal to the carrying capacity, K) of just over 1 300 Kt. The MSY catch was estimated by the model as 161 Kt and the f_{MSY} fishing effort was estimated as just over 30 000 standardised boat days (compare these MSY levels of catch and effort with the actual historical levels in Figure 11A).

According to the model, reducing the fishing effort levels to the f_{MSY} level of 30 000 units from 1968 onwards would have allowed the stock size to rebuild to B_{MSY} and thereafter have delivered the MSY catch. This would not have been achieved immediately, but only gradually over a number of years as the fishery reached equilibrium at that effort level. If a total allowable catch (TAC) was used as an output control instead of using effort controls, more care would have been needed to set the right TAC. With the stock size already below B_{MSY}, attempting to immediately take the MSY catch would have caused the fishery to continue to decline and eventually to collapse (see the dotted line representing the biomass projection for the 161 Kt MSY catch in Figure 11C). As shown by the other projections in Figure 11C, future TACs of 130 Kt and 140 Kt (below MSY) would have allowed the stock biomass to rebuild over several years to levels well above B_{MSY}. Taking the estimated ‘replacement yield’ of 151 Kt would, as expected, have maintained the population at the 1968 level of 489 Kt. A good TAC scenario would have been to take a catch of 140 Kt for 10 years up to 1977 by which time the biomass would have rebuilt to B_{MSY}; after this, the MSY catch of 161 Kt could have been taken sustainably. These alternative TAC scenarios could have been presented to managers in a strategic assessment report. As indicated above, MSY and its related reference points should be seen as limits rather than targets in order to make allowance for uncertainties in the behaviour of the resource, the estimates and the achievable levels of compliance.

Remembering the uncertainty in the assessment, managers should also be presented with the confidence intervals (CIs) of the predictions. CEDA reports CIs both for parameter estimates (including the reference points) and for the projected future biomasses. With a fifty percent confidence interval for the stock projection of a 140 Kt TAC, for example, it would have been predicted that there was less than a 25% chance (the lower percentile of a 50% CI) that the stock biomass would be below 500 Kt on reaching the future equilibrium (see FTP 487, Figure 8.3). If the 161 Kt MSY catch had been taken from 1977 onwards, the lower 50% CI drops below zero in 1987 indicating a significant risk that the fishery could still collapse with that scenario. As suggested above, different TACs and confidence intervals could thus be tested to find precautionary levels of the TAC based on selected limit reference points (e.g. B_{MSY}) and risk tolerances (e.g. a 10% chance that biomass after a certain year will be below B_{MSY}).

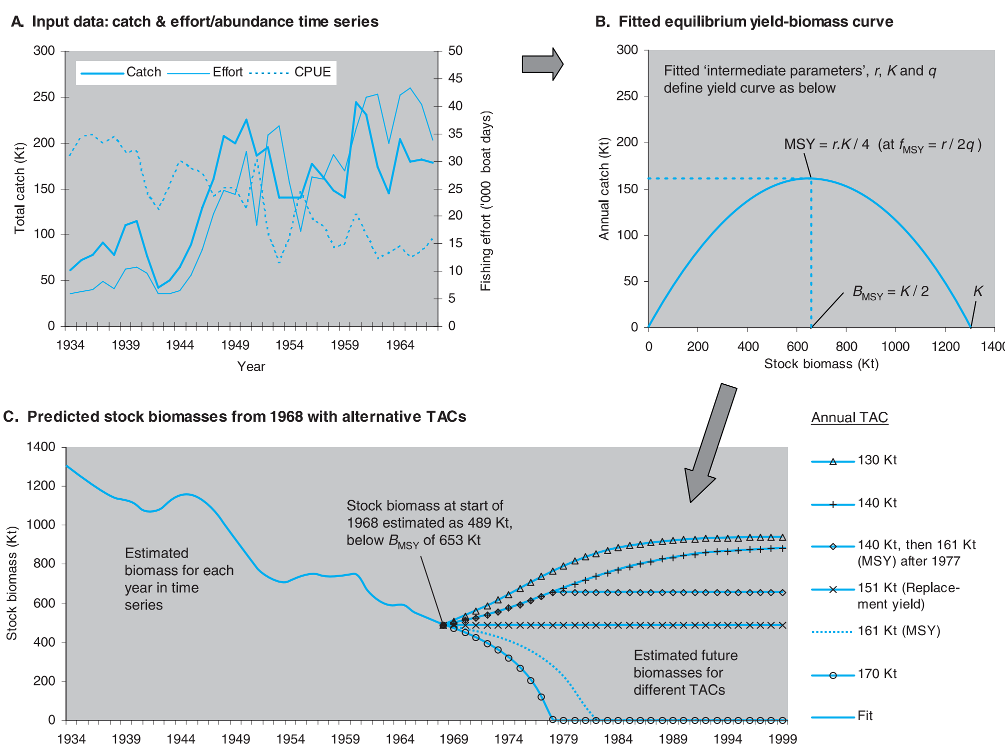

Figure 11. Illustration of the 'biomass dynamic' approach to stock assessment using the Schaefer production model in CEDA and the CEDA Tuna tutorial data set. Note that the CPUE index (dotted line) in graph A is re-scaled to fit on the graph with no y-scale given

Annex 5. Using the ParFish tool in data-limited situations and co- management

Stock assessment tools such as CEDA and Yield use standard fishery data (see Section 2.3) to estimate management parameters. Where the data for these methods are limited, as is often the case, parameters can be estimated only with low precision. Data may be limited in the following situations:

- In new fisheries (having only a few years' data);
- In fisheries where historical data have not been collected (e.g. due to financial constraints); or
- In lightly exploited fisheries (having no data on the response of the fishery under heavy exploitation).

In these common situations, a 'Bayesian' stock assessment approach may be used to overcome some of the limitations of the data sets. The Bayesian approach is not a new stock assessment model, but a more flexible way of fitting models and making decisions that can make use a range of different sources of information at the same time (see Box 28).

The FMSP ParFish software uses a Bayesian fitting method to provide management advice based on the Schaefer type of biomass dynamic model [1]. The same catch and effort (or abundance) data can be used to fit the model in ParFish as in CEDA. With its Bayesian basis, ParFish can also use additional information to improve the assessment in two quite different ways. These are illustrated in Figure 12 and described in the following sections.

The ParFish software uses a Bayesian method to fit a biomass dynamic model and can improve the analysis by using different types of input data

Box 28. What is the Bayesian approach?

Bayesian analyses are all about probabilities. As a simple example, if you are tossing a coin, you might expect an equal chance that it will come down heads or tails. We might then say that each of the two possible outcomes has a ‘probability’ of 0.5. With our Schaefer production model, we might estimate that the carrying capacity, *K*, is say 1,300 Kt as in the example in Annex 4. Since there is also a good chance that it could be a bit more or less than this, we could say that *K* has a ‘probability distribution’ centred on 1,300 Kt, with a spread of other possible values around that central value (something like a normal distribution but maybe not symmetrical). In a Bayesian analysis, we can combine ‘prior probability distributions’ for such parameters with any raw data that we have (such as a catch-effort time series) to calculate the ‘posterior distributions’ of the parameters. These are then used to provide management advice, also often based on probability distributions. If we are managing in a precautionary way, for example, we can look at the distributions for different catch or effort scenarios to find which one has a probability that we are prepared to accept of the stock size falling below a given limit reference point (e.g. B_{MSY}).

What are the advantages of using a Bayesian approach?

In data limited situations, the Bayesian approach can help to reduce the uncertainty in the analysis. In the biomass dynamics model, for example, the model parameters *K* and *r* are often strongly negatively correlated, with a ridge of pairs of values giving almost equally good fits. In this situation, independent ‘prior’ estimates of likely values for *r* can be entered to help pin down the most likely corresponding values of *K*.

A second advantage of the Bayesian approach is that it provides a good way of integrating all the uncertainties in an assessment, to produce management advice for the key factors of interest – i.e., the probability distributions (the range of likely values) of the performance indicators, for each management action being considered. Where normal ‘sensitivity analyses’ are used instead of Bayesian methods (i.e., changing a single parameter at a time and re-calculating – see Section 5.4), you may find it difficult to present the results for all of the different combinations of parameter and model uncertainties. For further details on this, see FTP 487, section 4.6.1.

[1] *The Schaefer production model is referred to in the ParFish documentation as the ‘logistic’ model. Future versions of the ParFish software may include other model forms.*

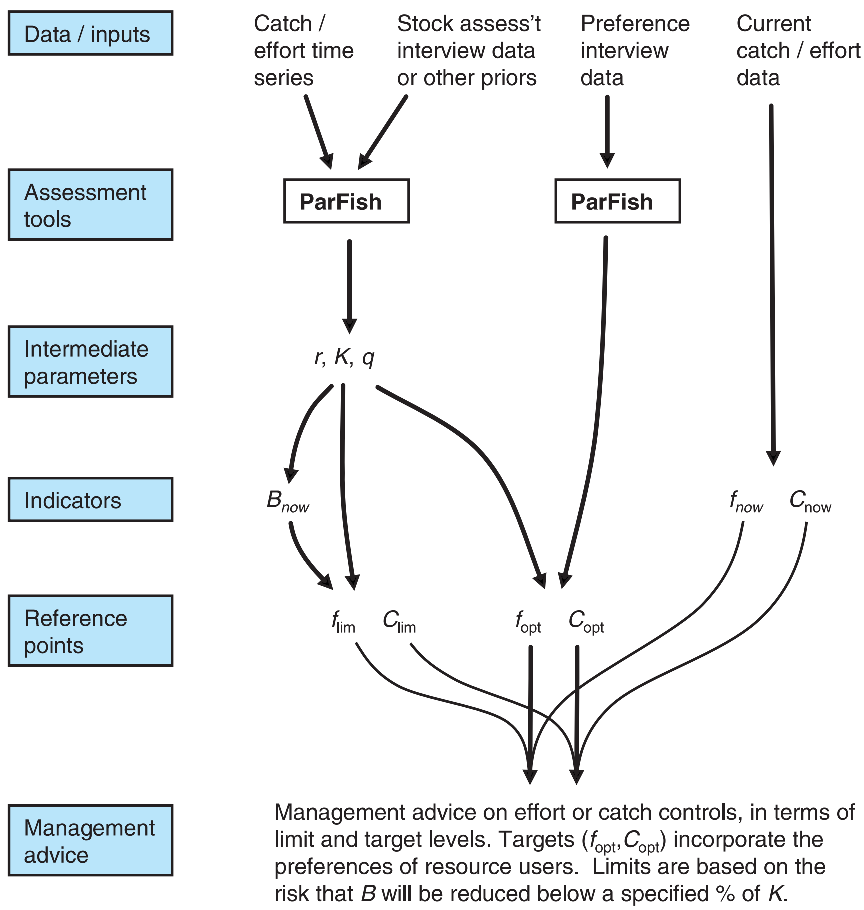

Figure 12. Information flows in the ParFish approach to stock assessment (see text, and compare with the CEDA process shown in Figure 10). ParFish can also give advice on refuges / no take zones (not shown here)

How can ParFish help in data-limited situations?

In data-limited situations, the estimates of the Schaefer model parameters may be improved with various types of supplementary data or information. Using the example in Box 28, you could search for published estimates of the population growth rate, *r*, either for related species, or for other geographic stocks of the same species. These could then be entered as prior distributions in ParFish. You could also do some 'depletion' fishing experiments to estimate the size of the fish stock in small localised areas,

If you have only a few years' C/E data, ParFish can use other 'prior' knowledge to improve the fit, including interviews with fishermen such as discrete bays or coral reefs. These could be averaged and multiplied up to the total area inhabited by the stock to give a rough independent prior for the current stock size, B_{now}.

Where no catch/effort data are available at all, approximate estimates of the parameters may also be derived from the local ecological knowledge of fishermen, research scientists or other stakeholders. An interview process is provided in the ParFish toolkit by which the parameters of the Schaefer model can be estimated based on simple questions about current and historical catches, and expected catch rates and recovery times if fishing was stopped. Most older fishers will have experience on changes in their stocks that can help this process even when no formal data have been written down or collected.

Although these interview-based priors may not be exactly right, they do allow fishers to express their current expectations or beliefs. These can be combined with any available catch/effort data (using the Bayesian approach), and improved in future as the fishery develops. Management advice based on such an analysis will still usually be better than no management at all (see the Turks and Caicos example analysis in the ParFish chapter in FTP 487).

Using ParFish in a co-management situation

By also interviewing fishermen on their 'preferences' about catch and effort, you can estimate optimal management recommend-ations for the fishery

In addition to using stock assessment interviews to help estimate the intermediate parameters, ParFish also allows you to include prior information on the fishermen's 'preferences' for the fishery. A second interview proforma is provided in the toolkit for making preference interviews. In these interviews, fishers rank possible outcomes in their fishery, measured as relative changes in their catch and effort. Would they rather have more catch even if it meant working harder? Or would they prefer their current catches but for less work? As shown below, these preference data can be combined with the stock assessment analysis in ParFish to estimate the 'optimal' management measures for your fishery.

Both these preference interviews and the stock assessment interviews can be very useful in a co-management situation, as the fishermen will be more likely to agree to the management recommendations if they can see that they have been adjusted to achieve *their* preferences, at least, as far as possible. Even if the stock assessment interview results are not considered to be very reliable, there may be considerable political advantage in involving fishers in an assessment, so they can see that their views are being taken into account.

Providing management advice from ParFish

ParFish estimates both target reference points that are adjusted for the fishers' preferences, and limit reference points that have defined risks of depleting the fish stock

The Schaefer model in the current ParFish software can provide strategic or tactical advice on effort controls, catch quotas or closed areas. The primary aim in ParFish is often to set a 'best' or optimum level for the chosen management measure or control. This would usually be used as a target reference point. These targets provide guidance on the social or economic goals, as they are adjusted to include the prior data from the fishermen's 'preference' interviews. Where effort or catch controls are selected as the management measures, ParFish refers to these optimal targets as f_{opt} and C_{opt}. ParFish can also give simple guidance on how closed areas might contribute to the management of the fishery, if they provide effective 'refuges' for the fish stock (see Box 29).

Box 29. How does the 'refuge' or 'closed area' option work in ParFish?

The 'refuge' control in ParFish sets a user-defined proportion of the stock biomass as being protected from fishing. This may be achieved through a closed area, but you should bear in mind that closing X% of the fishing grounds will not necessarily mean that the same X% of the fish biomass is effectively protected, as is assumed by the ParFish model. This will also depend on factors such as the degree of movement of the population and the relative densities of the stocks in the closed area and the fished areas. In the ParFish model, the assumed 'protected' stock inside the refuge will grow to the same X% of the unexploited stock size, *K*, regardless of the fishing pressure outside the refuge. ParFish does not model the migration of fish between the protected and fished stocks, but simply includes the extra biomass produced in the refuge each year in the total production of the population. The refuge model in ParFish is thus a simple representation of what might be expected from introducing a closed area control in a fishery; a cost to the fishermen in limiting the availability of the stock hopefully compensated by a benefit in building up the productive biomass. For further details, see the ParFish help files.

It is important to note that the ParFish model assumes that the refuge is fully 'effective'. If it is not (e.g. because some fish migrate out of the refuge and get caught), then its real contribution to the fishery may be less than predicted by ParFish. To model the effect of the closed area more rigorously would need a detailed understanding of behavioural and ecological factors such as, the rates of movement of both eggs and larvae from the refuge, and the migratory behaviour of juvenile and adult fish. Such behaviour may change with environmental conditions between years and be quite complex in some fisheries such as in floodplain rivers. Reducing these complexities to defining a simple proportion of stock and range is thus a simplification of the real situation, as with any other fishery model. Given its formulation, the ParFish refuge option would be better regarded as a useful addition to the biomass dynamic production model, than as a reliable means of predicting the effect of closed areas in the absence of other measures. In any case, relying only on closed areas or refuges is unlikely to achieve economic and social objectives – a variety of controls, rather than relying on any single control, will generally best reduce risks.

In practice, then, just as with any other stock assessment model or tools, the refuge or closed area option in ParFish should only be used after careful consideration of the assumptions that are being made and the uncertainties that are involved. Initial management guidance should always be checked by monitoring the actual results that are achieved in future years, after the advice has been implemented.

Bearing in mind the biological constraints imposed by the natural productivity of the fish stock, ParFish also allows you to define limit reference points for each of the controls that would have a specified risk (e.g. 10%) of reducing the stock size to a user-defined fraction of the unexploited stock, $B_{infinity}$ [1] (e.g. at 50% of $B_{infinity}$ or K, corresponding to the MSY point of the Schaefer model).

ParFish analyses are presented as the selected performance indicators plotted relative to the reference points using integrated graphical outputs. An example showing the levels of the catch quota management control that would achieve each of the target and limit reference points is given in Figure 13 below. As a general rule, you should aim to ensure that your optimal target reference point is on the safe side of the limit reference point. You should also note, however that the limit reference point may sometimes be very restrictive on the fishery simply due to the high level of uncertainty in the analysis. In these cases, which could be recognised by a very flat probability distribution, you may be able to make the recommendations less restrictive by collecting more or better data and re-running the analysis (see ParFish Guidelines for further details).

[1] The term, $B_{infinity}$ or B_{inf} used in the ParFish documentation is equivalent to the carrying capacity or K of the Schaefer production model, used elsewhere in this guidebook.

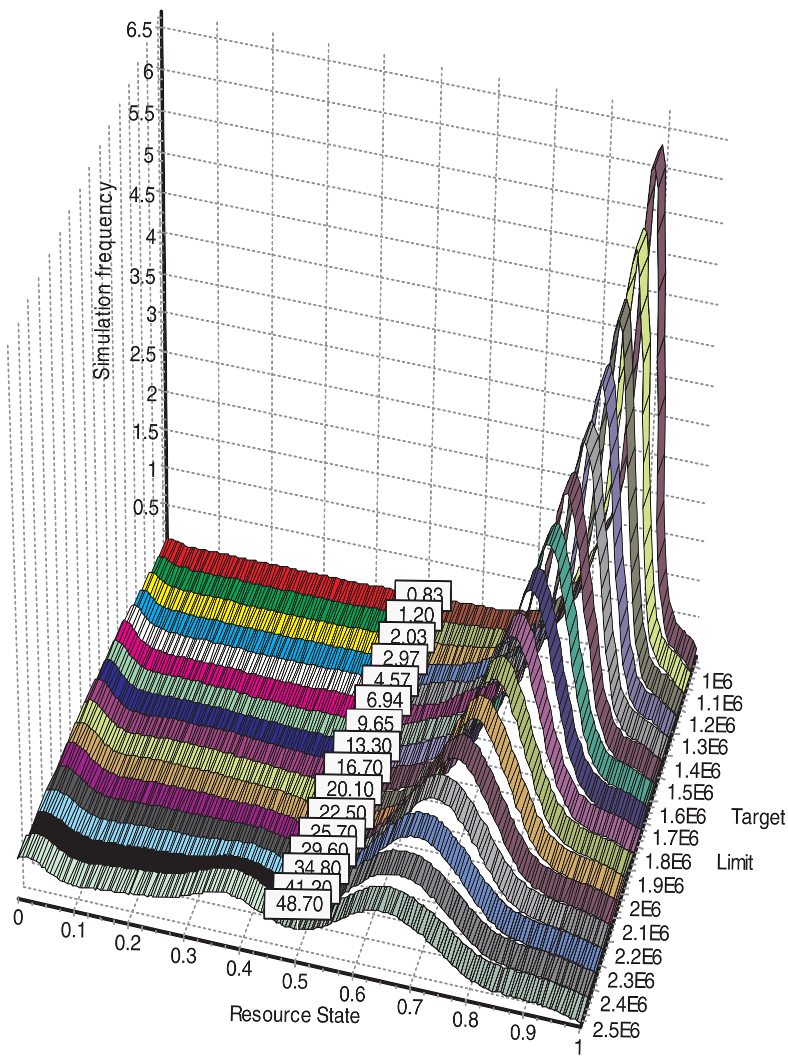

Figure 13. Example output from ParFish showing the stock state as a probability function for different levels of the management control, in this case a catch quota (shown on the right axis). The number labels on each curve give the probability (as a percent) that the stock will become overfished at each level of the quota. Overfishing is defined as the stock falling below a user-defined proportion of the unexploited level (50% of B_{inf} or K is used in this example). As the quota increases, not only does the average stock state (i.e. the peaks of the curves) decrease in size, but the state becomes increasingly uncertain, as illustrated by the flatter probability distributions. The Limit catch in this example is a quota of approximately 1.8m units, having a chance of less than 20% (as selected) of falling below the 50% B_{inf} threshold. The Target quota, incorporating fishers preferences, at 1.6m units, is safely inside the estimated Limit quota level.

The Writing Team

Daniel Hoggarth
Managing Director
Scales Consulting Ltd, a fisheries consultancy company.
66b Creffield Road, London W3 9PS, UK.
Email: dhoggarth@btinternet.com

Christopher Mees
Research Director

and

Catherine O'Neill
Senior Consultant
Marine Resources Assessment Group (MRAG), an aquatic resources management consultancy.
MRAG Ltd, 18 Queen Street, London W1J 5PN, UK.
Website: www.mrag.co.uk
Email: enquiry@mrag.co.uk

James Hindson
Head of the International Project Unit, FSCEE
Field Studies Council, a UK based Environmental Education NGO,
Preston Montford, Montford Bridge, Shrewsbury, SY4 1HW, UK.
Website: www.field-studies-council.org
Email: fscee@field-studies-council.org

Mohan Krishna
Programme Officer
Centre for Environment Education,
Nehru Foundation for Development,
Thaltej Tekra, Ahmedabad 380 054, Gujarat, India
Website: www.ceeindia.org
Email: mohan.krishna@ceeindia.org

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