A fish population rebuilding framework to control multispecies, multistock, and/or multiarea fisheries for medium to longterm management purposes

Joachim Paul Gröger[1] and Rodney Alan Rountree

(JPG) and (BR) School for Marine Science and Technology (SMAST), University of Massachusetts at Dartmouth, 706 South Rodney French Boulevard, New Bedford, MA 02744-1221, U.S.A., jgroeger@umassd.edu

(RAR) Marine Ecology and Technology Applications, Inc (META Inc), 23 Joshua Lane, Waquoit, MA 02536, U.S.A., rrountree@fishecology.org

Corresponding Author: Joachim Paul Gröger, Institute for Sea Fisheries, Federal Research Centre for Fisheries, Palmaille 9, D-22767 Hamburg, Germany, Phone +49 040 38905-266, Fax +49 040 38905-263, email joachim.groeger@ish.bfa-fisch.de

[1]| Current address: Institute for Sea Fisheries, Federal Research Centre for Fisheries, Palmaille 9, D-22767 Hamburg, Germany; phone +49 (0)40 38905-266, Fax +49 (0)40 38905-263; email joachim.groeger@ish.bfa-fisch.de

Abstract

The key objective in fishery management is to maximize landings (or economic value) on a sustainable level. This can be managed using either effort or quota control mechanisms. Sustainability can be interpreted in different ways and is subject to different constraints. Traditional techniques are often applied in equilibrium settings and relate to maximizing production, using a Y/R or SSB/R function. These techniques have been developed in a single-species setting (see however MSVPA) even though many fisheries take many species simultaneously. But even in a single species setting, the traditional techniques leave much to be desired as these techniques do not always yield a clearly defined maximum. In addition, the theory underlying the techniques is brought into question by the very large variability in real data fitted to any of the techniques.

The current paper will outline the fundamentals of a stock rebuilding framework with clear optimality by controling fishing effort (or fishing mortality) and maximizing landings (or economic value) based on nonlinear optimization using algorithms from economical control theory. For illustration purposes we give a simplified quasi-realistic multispecies example with five groundfish species.

Introduction

The improvement of fishery-management information is a complex undertaking due to

- complexity of fishery management models
- uncertain statistics of the observations and sampling procedures and
- the role of the ocean environment.

These elements are also interrelated. For instance, the complexity of fisheries management stems partly from the dynamic nature of the marine environment. But also numerous interest groups are involved and thus interact with different objectives. At present, the fishery management is usually performed in four major steps (see Fig. 1):

(1) collecting population relevant data (commercial, market sampling and research survey data)

(2) estimating the relevant population parameters (stock abundances, fishing mortalities, etc.)

(3) predicting the future and simulating scenarios based on different management options and on the results of step 2 (catch-effort or biomass-effort relationships) (see Fig. 2)

(4) under the given circumstances, taking the most plausible result(s) of step 3 as optimal management strategy.

Currently, the commercial catch information is calibrated by survey information as surveys are to some extent standardized and normalized. The estimated parameters are usually stock sizes in numbers and fishing mortalities by age and, dependent on the type of model, sometimes other parameters such as catchabilities. Beside problems such as data inconsistency, their relatively limited temporal and spatial resolution, ignoring the environment, not integrating species interactions, one major problem seems the transition to get from retrospectively estimated parameters to a future oriented medium to longterm management. Potentially, this can be done either by using the power of a retrospectively oriented prediction model to forecast the future, or by using some tool for generating scenarios. Traditonally, these scenarios are generated using some kind of analytical MSY approach usually being based on some type of catch and effort curve. This paper is intended to bridge this gap introducing a numerical procedure using a non-linear optimization algorithm which we adopted from econometric control theory. The approach is fairly open and intended to be a framework for rebuilding stocks. Because of it's open framework nature it can incorporate many aspects as outlined above and thus can overcome some of the important problems.

Methods

The theoretical framework for our target rebuilding approach

The key objective in fishery management is to control fishing effort in order to maximize landings (or economic value) on a sustainable level. However, sustainability can be interpreted in different ways and is subject to different constraints. To accomplish a sustainable fishery a set of control mechanisms has been developed by the various management agencies. These mechanisms include:

- fishing capacity restrictions: fishing permits limit the number of fishing vessels, the size of a vessel, the number of crew a vessel can carry, and the length of time a vessel can fish (fishing effort such as the number of days-at-sea (DAS))
- gear restrictions: the type of a gear, it's size, it's mesh size, the number and length of hooklines or gill nets used, the number of hooks per meter hookline, etc.
- area specific restrictions: controlling where, when, and for how long fishing can take place

- catch restrictions: quotas (total allowable catches (TACs)), limitations regarding by-catch ratios, discarding, highgrading, etc.

Our rebuilding model addresses step (3) of the stock assessment and management procedure as mentioned in the introduction, i.e. the simulation of scenarios based on varied management options to derive the optimal yield-effort constellation. But unlike traditional approaches, which derive a MSY proxy by means of the catch-effort diagram (i.e. some proxies for MSY and F_{MSY}), we will use tools adopted from economical control theory or nonlinear econometrics to develop the optimal management strategy, for instance, for groundfish stocks (see our example later in this text). This perspective also allows us to make the precautionary approach an integral part of the control procedure.

The idea and basic outline of the rebuilding model is as follows (see Fig. 6): suppose we have a planning horizon of 10 years, encompassing the years 2005 to 2014. This period starts with an initial multi-area, multi-species and age-disaggregated biomass in 2004 (i.e. biomass resolved by area, species, age class) and ends with a target biomass in 2014. Although the rebuilding period can be less than the planning horizon and may be variable among species, herein we define them as equivalent and the same for all species. The initial biomass is the last retrospective year's biomass "estimated" by the modeling procedure used (i.e. by methods such as ADAPT (see Gavaris 1990), statistical catch-at-age models (Deriso & Quinn 2???), or the Kalman filter (see, for instance, Harvey 1989)). The target biomass is the rebuilding biomass to be met at the end of the rebuilding period which is set by the fishery managers. This could be, for instance, the target biomass derived from the precautionary approach (B_{PA}). We then track the annual biomass development subject to fishing activities during the rebuilding period (planning horizon). As input we thus allow some fishing effort (for instance, in terms of days-at-sea; or some fishing mortality) and will get some annual yield (split up by area, species, and age class of concern) as output. These fishing activities are restricted by boundaries for the fishing effort (or the fishing mortality, for instance, using F_{MSY} as some upper limit). Such constraints can arise due to biological limitations resulting, for instance, from bycatch, recruitment, rebuilding issues, etc.. Under this framework the optimal solution in terms of effort allocation will be determined by maximizing the total yield subject to these constraints (i.e. within these effort boundaries). The framework must be set by fishery managers through the definition of limiting fishing effort (or fishing mortality values) and rebuilding targets. In other words, the objective is to find the optimal constellation of fishing effort f (or fishing mortality F) values by area, species or stock, age, and year which maximizes the total yield (in physical or economical units) at the end of the planning horizon (or rebuilding period).

Hence, the control or instrument variable is the fishing effort f (or the fishing mortality F), the objective function is the total yield in physical or monetary units being subject to maximization, the constraints are, for instance, that:

- "one ton of haddock will have X tons cod as bycatch so that the catch of cod must be limited to 50 kg per trip" and/or
- "by 2014 the SSB of cod must be equal or larger than the set rebuilding SSB target" and/or
- "by 2007 the SSB of haddock must be equal or larger than the set rebuilding SSB target" and/or
- "the fluctuation of the annual total catch should be minimal to ensure a relatively stable income for the fishermen".

Closed areas or seasons can simply be implemented as effort constraints by setting days-at-sea to 0 (DAS = 0) either constantly or periodically in some area of concern. Thus, the principle idea is to simulate scenarios and iterate model parameters as long as these are nonoptimal in terms of an optimization criterion.

Our rebuilding framework can be implemented numerically using algorithms based on methods of nonlinear optimization. Thus either maximization or minimization algorithms can be used to optimize the objective function; in case of minimization algorithms only the sign of the optimization criterion must be reversed as the goal is maximization of the function. A large set of different algorithms with different requirements do exist and can be found, for instance, in literature related to numerical mathematics; but also program implementations (procedutres, subroutines), for instance, for MATLAB or SAS do exist. Anyhow, during the search process, an iterative process is used to return the objective function's value for each iterated alternative. This iterative approach is sometimes called simulation, so that the entire algorithm can also be called simulation based optimization (Azadivar 1992). It is usually necessary to initialize the algorithms by start F (or f) values. Some of the nonlinear optimization algorithms (e.g. the Nelder-Mead or the Dual-Quasi-Newton Optimization Algorithms) function without the need of specifying derivatives (e.g. without implementing a Hessian or Jacobian matrix). We use SAS version 9.1.3 , specifically the integrated matrix language SAS/IML (SAS Institute Inc. 1999), for solving the equations because of its ability to manipulate large-scale matrices while at the same time having the simulation embedded into a macro-based statistical environment easily allowing an alteration of options and of carrying out sophisticated statistics.

For the following description of model features suppose we consider one species in one specific area which leads to the set of equations below. Note, although all subsequently stated model equations could be easily extended and implemented using age, year, area, and species disagregated values and thus subscripts, for convenience and legibility we suppress the subscripts for area and species in most cases presented herein except where necessary. In order to be illustrative, also the quasi-realistic example that we finally present in order to demonstrate the theory will focus on a simplified 5 species (6 stocks) situation in the Gulf of Maine and Georges Bank area. Parts of the theory as outlined below was already presented in an ICES paper (see Gröger *et al.* 2004).

On the computation of physical yield and its maximization - The central equation for calculating the annual (physical) yield per area and species is given by Baranov's catch equation (Baranov 1918)

$$
\begin{aligned}
&C_{a,y} = \frac{F^*_{a,y}}{Z^*_{a,y}} \times N_{a,y} \times (1 - e^{-Z^*_{a,y}}) \\
&\underline{\textit{with}} \\
&C_{a,y} : \textit{catch in numbers fish per age class and year} \\
&Z^*_{a,y} = F^*_{a,y} + M_a \\
&F^*_{a,y} = \hat{F}_{a,y} \times S_a \\
&\qquad (\textit{i.e. } F^*_{a,y} \textit{ takes into account the age-specific selectivity pattern } S_a) \\
&\hat{F}_{a,y} : \textit{during the maximization process estimated fishing mortality} \\
&a : \textit{age} \\
&y : \textit{year}
\end{aligned}
\qquad (1)
$$

S_a can either be an element of a matrix of empirical selectivity values or might be specified by some selectivity function.

Multiplying the catch in numbers by a body weight vector W with age-specific elements W_a gives the yield in biomass (kg):

$$
\begin{aligned}
&Yield_{a,y} = C_{a,y} \times W_a \\
&\underline{\textit{with}} \\
&W_a : \textit{weight matrix}
\end{aligned}
\qquad (2)
$$

The weight vector W may either contain empirically derived mean weight values W_a by age and species or values W_a specified by some empirical weight function.

Totaling this up gives the total annual yield that also forms the major component of the objective function (optimization criterion) to be maximized:

$$Total\ Yield = \sum_a \sum_y Yield_{a,y} \quad \textbf{(3)}$$

Since we have to make sure that the total biomass at the end of the rebuilding period matches the target biomass, some penalty function (per species) must be incorporated (if the rebuilding period varies for different species then the summation takes place over different time horizons)

$$\begin{aligned}
&Penalty\ term_{species} = \max\ (0,\ B^{(target)}_{species} - B^{(total)}_{species}) \\
&\underline{with} \\
&B^{(target)}_{species} : target\ (rebuilding)\ biomass\ per\ species \\
&B^{(total)}_{species} : total\ biomass\ per\ species\ at\ the\ end\ of\ the\ rebuilding\ period
\end{aligned} \quad \textbf{(4)}$$

I.e. we penalize differences larger than 0 and ignore negative differences. This can be judged as some further kind of constraint (multiple constraints beside constraining the f or F values). The penalty term can be extended by multiplying it with a species-specific coefficient $\theta_{species}$ in order to weight some species over others. Setting the elements of the penalty coefficients' matrix to 1 gives every species the same weight. The objective function then becomes

$$Objective\ function = Total\ Yield + \left(\sum_{species} - (\theta_{species} \times Penalty\ term_{species}) \right) \quad \textbf{(5)}$$

This functions means that the total yield will be maximized while at the same time the values of the species related penalty terms are minimized (i.e. the sum of negative differences will be minimized as we maximize negative values).

In order to stabilize the expected yearly catches (keeping the catch stable over time is more attractive for fishermen as it keeps their income constant in time) this objective function can be further extended by introducing a smoothing term

$$Smoothing\ term_{species} = \sum_{y=1}^{end\ of\ rebuilding\ period_{species}} abs\ (Yield_{species}^{(desired)} - Yield_{y,\ species}\ )$$

<u>*with*</u> **(6)**

$$\begin{aligned} &Yield_{species}^{(desired)} : a\text{-}priori\ set\ desired\ level\ of\ yield\ per\ species \\ &Yield_{y,\ species} : annual\ yield\ per\ species (aggregated\ over\ age) \end{aligned}$$

In contrast to the penalty term above here we penalize absolute differences, i.e. not only positive but also negative differences as we want to reduce the fluctation in general. The smoothing term can be considered one component of multiple constraints. As part of the objective function it will be subtracted from the given total yield and thus becomes minimized. Again this function can be extended by multiplying it with a species-specific weighting coefficient $\lambda_{species}$ in order to give some species priority over others. The modified objective function to be maximized then becomes

$$\begin{aligned} Objective\ function = \ & Total\ Yield \\ & + \left(\sum_{species} - (\theta_{species} \times Penalty\ term_{species}) \right) \\ & + \left(\sum_{species} - (\lambda_{species} \times Smoothing\ term_{species}) \right) \end{aligned} \qquad \textbf{(7)}$$

This functions means that the total yield will be maximized while at the same time the summed negative terms will be minimized (maximization of a negative value). Rather than using an arbitrary $Yield_{y,\ species}{}^{(desired)}$ in Eq. (6) an annual average yield may be used although this would increase the computer runtime somewhat as the average value will change during each iteration.We should keep in mind that components of Eq. (7) may be area-specific and thus may be added up over area to give the overall objective function. It can be further inferred that not only the rebuilding target but also the rebuilding period might be different for different species. In such a case the summation in Eq. (3) (2nd sigma sign) but also in Eq. (6) takes place over a different number of years for different species.

On the computation of economic yield and its maximization - An alternative objective function (optimization criterion) based on economical rather than physical yield can be derived following the subsequent procedure. Multiplying the physical yield in biomass (kg) with the species-specific unit price and totaling this up gives the total annual economical yield that then forms the major component of a modified objective function:

$$\begin{aligned} &Total\ Yield = \sum_a \sum_y Yield_{a,y} \times P_y \\ &\underline{with} \\ &P_y : unit\ price\ (price\ per\ kg) \end{aligned} \tag{8}$$

Here the unit price may differ by species but usually not by area (i.e. it can be considered constant, for instance, for different areas on Georges Bank). Depending on the species and on whether the fish is used for consumption or not the unit price may also vary by other factors such as quality categories or size groups. Furthermore, the unit price may change with the amount of caught fish (economical rule of supply and demand). This may require to use a feed back instead of a simple price function (interdependent or simultanous price model) for calculating the unit price dependent on the amount of fish landed. As for the physical yield we can add penalty and smoothing terms to the economic yield. If information on costs is available the objective function might be modified by maximizing the profit as a criterion instead of the income:

$$Profit = Total\ Yield - Total\ Costs \tag{9}$$

Also here, we should keep in mind that Eq. (8) contains species- and area-specific elements and thus must be further added up over species and area to give the overall objective function.

On the computation of stock sizes and incorporation of recruitment - Eq. (1) contains elements $N_{a,y}$ of a stock size matrix *N*. Except from $N_{1,y}$ age-specific stock sizes will be modelled as

$$
\begin{aligned}
&N_{a,y} = N_{a-1,y-1} \times (1 - e^{-Z^*_{a,y}}) \;; \quad \textit{for } 1 < a < age_{\max} \\
&\underline{\textit{with}} \\
&Z^*_{a,y} = F^*_{a,y} + M_{a,y} \\
&F^*_{a,y} = F_{a,y} \times S_a \\
&\qquad (\textit{i.e. } F^*_{a,y} \textit{ takes into account the selectivity pattern } S_a) \\
&a : \textit{age} \\
&y : \textit{year}
\end{aligned}
\tag{10}
$$

$N_{1,y}$ will be specifically calculated as recruitment of the preceding year either using a density depending or independent stock-recruitment function; in case of density dependence we use the Ricker approach for estimating $N_{1,y}$ (Ricker 1954), i.e.

$$
\begin{aligned}
&N_{1,y} = R_{y-1} \\
&\underline{\textit{with}} \\
&R_y = R_1 \times SSB_y \times e^{-R_2 \times SSB_y} \\
&SSB_y \quad : \textit{annual spawning stock biomass (index)} \\
&R_y \quad : \textit{annual number of recruits (index)} \\
&R_1,\, R_2 \quad : \textit{function parameters to be estimated}
\end{aligned}
\tag{11}
$$

In case of a weaker density dependence we will use the Beverton-Holt approach for estimating $N_{1,y}$ (Beverton-Holt 1957), i.e.

$$N_{1,y} = R_{y-1}$$

with

$$R_y = \frac{SSB_y}{SSB_y + g \times R_{\max}} \times R_{\max} \qquad \textbf{(12)}$$

SSB_y : *annual spawning stock biomass (index)*
R_y : *annual number of recruits (index)*
$R_{\max}$: *asymptote of the recruitment curve*
g : *slope*

In both cases simple linearizations exist. If recruitment shows some dependence on environmental factors we will use an extended recruitment function (see Hilborn & Walters, 1992); for example, using a linearized version of the Ricker S/R relationship the effect can be incorporated as a linear combination turning the simple regression model into a multiple regression one:

$$\ln\left(\frac{R_y}{SSB_y}\right) = \ln(R_1) - R_2 \times SSB_y + c \times E_y$$

or **(13)**

$$\ln\left(\frac{R_y}{SSB_y}\right) = \ln(R_1) - R_2 \times SSB_y + c \times (E_y - \bar{E})$$

E_y is some environmental factor such as temperature, c is some regression coefficient, R_1 and R_2 have the same meaning as in the Ricker curve above. The second part expresses the environmental factor E_y relative to its average which may in some cases easier to interprete.

Anyhow, the recruitment functions given above can be easily replaced by other types of recruitment functions such as segmented regression approaches or simply by conditional vectors of discrete empirical values.

On the computation of biomass and spawning stock biomass - The spawning stock biomass $SSB_{a,y}$ will be calculated taking into account the age-specific maturity and weight pattern

$$SSB_{a,y} = N_{a,y} \times W_a \times Mat_a \qquad \textbf{(14)}$$

which, if summed up over age, is giving the total annual spawning stock SSB_y. Consequently, the biomass $B_{a,y}$ is being derived by

$$B_{a,y} = N_{a,y} \times W_a \qquad \textbf{(15)}$$

which, if summed up over age, gives the total annual biomass B_y.

On the incorporation of technical and biological interactions - Species interactions can be addressed in different ways, dependent on whether we consider technical (e.g. bycatch issues) or biological interactions (e.g. predator-prey interactions). Even then further differences in approaching this issue do exist. Technical interactions can be incorporated using a simple bycatch matrix containing values of observed proportions (ratios per target species) of caught species sorted by target species in the fishery. If we at the same time take into account the age-specific selection pattern, this then leads to the following re-formulation of the fishing mortality problem

$$\begin{aligned}
&F^*_{a,y} = \hat{F}_{a,y} \times S_a \times BC_a \\
&\textit{and} \\
&Z^*_{a,y} = F^*_{a,y} + M_a \\
&\underline{\textit{with}} \\
&BC_a : \textit{age-specific bycatch} \\
&\hat{F}_{a,y} : \textit{during the maximization process estimated fishing mortality} \\
&S_a : \textit{age-specific selectivity pattern} \\
&a : \textit{age} \\
&y : \textit{year}
\end{aligned} \qquad \textbf{(16)}$$

The multi-species interactions on recruitment level can be incorporated in a number of different ways, for example, by using a linearized version of the Ricker S/R relationship for haddock in which 2-year old cod feeds on haddock recruits (see Hilborn and Walters, 1992)

$$\ln\left(\frac{R_{y,\ haddock}}{SSB_{y,\ haddock}}\right) = \ln(R_1) - R_2 \times SSB_{y,\ haddock} + c \times (cod\ density)_{a=2} \qquad \textbf{(17)}$$

Also incorporating predator-prey relationships on a population level in a later stage is in principle not difficult; for example, this can be done by splitting up the natural mortality into two components such as

$$\begin{aligned} &M_a = M_{a,\ predator\ species} + M_{a,\ residual} \\ &\underline{with} \\ &M_{a,\ predator\ species}: \textit{natural mortality caused by predation through a predator species} \\ &M_{residual}: \textit{natural mortality caused by other reasons} \end{aligned} \qquad \textbf{(18)}$$

The real difficulty arises from the question, how to estimate the natural mortality components in terms of model parameters. In order to do so, we will partly consider species correlations based on our acoustic-optic measurements. Simultanously, as in case of the traditional MSVPA we will *inter alia* consider stomach contents, consumption rates, etc.. Both sources of information will be synchronized to derive empirical (synoptic) relationships between species correlation coefficients and predator mortalities.

On the conversion of fishing effort into fishing mortality - The conversion of fishing effort f (for instance, DAS) into fishing mortality F is another important issue to be considered. The reason for this is, that in contrast to fishing effort, which is the instrument variable whose values being set by fishery managers, is not the direct model parameter to be estimated and optimized. This is the fishing mortality F. We thus have to take into account the catchability q which is the interfacing coefficient between both quantities, i.e.

$$F = q \times f \qquad \textbf{(19)}$$

The catchability includes both biological and technological effects that are sometimes formally decomposed into the two separate components

$$q = q^{(availability)} \times q^{(efficiency)} \qquad \textbf{(20)}$$

where the first component represents the availability of fish in the swept area of the bottom trawl, and the second a quantity which measures the gear efficiency. The availability is assumed to be biologically triggered, e.g. species, size (age), area and time dependent; whereas the efficiency is assumed to be ship, gear, species, size (age), and area (bottom trawls !) dependent. In most cases it is practically difficult or even unrealistic to determine q, never mind to decompose it in it's components. That is why researchers often consider both coefficents $q^{(availability)}$ and $q^{(efficiency)}$ as constants and set them to 1. However, the catchability could be derived from area- and time- disaggregated industry-based surveys that may be compared and calibrated with standardized NMFS (National Marine Fisheries Service) surveys. The basic idea would be to estimate the ratio (see for instance, Harley and Myers 2001, Walsh 1996)

$$\hat{q}_{species,area,y} = \frac{CPUE^{(industry)}_{species,area,y}}{C\hat{P}UE^{(survey)}_{species,area,y}} \qquad \textbf{(21)}$$

where the expected density values may be derived from scientific survey CPUE data using a krigging method (Stein 1999); these data may be taken, for instance, from NMFS. In the case that these data are not age-based, information from selectivity experiments could be used and the estimated catchability coefficient multiplied with the derived selectivity pattern to get an age dis-aggregated catchability, i.e.

$$\hat{q}^{*}_{species,area,a,y} = \hat{q}_{species,area,y} \times S_a \tag{22}$$

The uncertainties may be investigated based on bootstrapping procedures using stochastic rather than deterministic functions.

Fig. 4 below summarizes the linkages between the above described equations and thus gives an overview of the underlying numerical structure the control theoretical algorithm is build upon.

A quasi-realistic example for the Georges Bank/Gulf of Maine area

Data Material - On purpose, this example is supposed to illustrate a simplified implementation of the theory outlined above to foster its understanding. Suppose we want to manage 5 species on Georges Bank (GB) and in the Gulf of Maine (GOM) area where one species is splitted into two separate components (stocks). It thus focuses on haddock (GB), yellowtail flounder (GB), witch flounder (GOM and GB together), and American plaice (GOM and GB together) and distinguishes GB cod from GOM cod; all species/stocks are assessed and managed by the National Marine Fisheries Service (NMFS) located in Woodshole, MA, USA where GB and GOM witch flounder but also GB and GOM American plaice are each managed as one stock as it is difficult to separate both stock components from each other; we thus consider these also as one stock each. On the other hand, the two cod stocks (GB and GOM) are separately assessed and managed by NMFS; for computational reasons we apply a trick and consider them numerically as being two different species in order to allow a simplified implementation of the bycatch matrix further below. Most of the relevant stock data were taken from the latest report of the Groundfish Assessment Review Meeting (GARM) for year 2005

(NEFSC 2005).

In general, we base our scenarios on a planning horizon (rebuilding period) of 10 years, starting with year 2006. Because of year 2006 being the initial point we took all relevant species related data from year 2005. All data used are age dissolved consisting of abundance estimates, weight, partial recruitment, and maturity observations. The abundance estimates are based on VPA estimates derived from domestic commercial catch data as well as scientific surveys performed by NMFS. The other data used (weight, maturity, partial recruitment) stem either from market samplings or from technical experiments prior performed. Both activities were carried out by NMFS researchers.

The bycatch data used for the bycatch matrix are taken from an industry-based survey performed by the School of Marine Science and Technology (SMAST) (University of Massachusetts, New Bedford, MA, USA) mainly on Georges Bank (Rountree et al. 2005). The bycatch data are used to set up a non-symmetric diagonal matrix of technical interactions (see equation (16)) whose cell entries consist of normalized fractions of bycatches per each bycatch-species (column) and for each target fishery (rows); thus its diagonal contains exclusively ones; its off-diagonal values are larger than zero if technical interactions occur and being zeros if no interactions occur (in case of absolutely no-interactions this matrix is equivalent to a symmetric identity matrix with all off-diagonal values being zero); it is given here as follows

	bycatch species:					
target fishery:	GBCo	GMCo	GBHa	YtFl	WiFl	AmPl
cod GB	1.00	0.04	0.13	0.04	0.07	0.03
cod GOM	0.01	1.00	0.13	0.04	0.07	0.03
haddock GB	0.26	0.01	1.00	0.05	0.07	0.07
yellowtail flounder (GB)	0.12	0.01	0.04	1.00	0.02	0.03
witch flounder (GB+GOM)	0.48	0.02	0.06	0.03	1.00	0.14
American plaice (GB+GOM)		0.16	0.01	0.10	0.02	0 . 3 4

where the first two rows represent the two cod target fisheries (GB and GOM), and the remaining rows the target fisheries on haddock (GB), yellowtail flounder (GB), witch flounder (GB+GOM combined), and American plaice (GB+GOM combined). As we consider two different cod stocks we have to relax the usual definition of a technical interaction which normally is only applied to different species, but in this case also to two different populations. As we usually cannot distinguish between individuals of different populations or stocks of one species in the catch, we utilized results from a cod tagging program (see http://www.gmamapping.org/codmapping/20893). This allowed us to infer a percentage of 1% cod moves from the GOM area into the GB area and of 4% cod moves vice versa (see the two first rows and columns in the bycatch matrix above). We took these fractions as an estimate for how often GOM cod appears proportionally in GB cod catches and vice versa. As we have no data how cod technically interact with other species in the GOM area we assumed here the same pattern as in the case of the GB area although we know that this might be unrealistic as the species mix in the GOM area differs from that of the GB area. Anyhow, this example is supposed to be illustrative why we accept this simplifying assumption for now.

We then used the following estimated versions of recruitment functions, again taken from the most recent GARM report (NEFSC 2005):

Cod (GB):	R = 58569.90 × SSB / (182740.90 + SSB) (age 1 in thousands)
Cod (GOM):	R = 9854.36 × SSB / (7516.10 + SSB) (age 1 in thousands)
Haddock (GB):	if SSB < 75000 t then R = 9879 else R = 10615 (age 1 in thousands)
Yellowtail Flounder (GB):	if SSB < 5000 t then R = 13220

else R = 24444 (age 1 in thousands)

Witch Flounder (GB+GOM):	mean R = 32549.5 (age 3 in thousands)
American Plaice (GB+GOM):	mean R = 8813 (age 1 in thousands) .

The SSB rebuilding targets (in tons) to be reached at the end of the 10 years rebuilding period are defined here as species specific biomass reference point estimates (B_{MSY}) again taken from the 2005 GARM report (NEFSC 2005):

Cod (GB):	216780 t
Cod (GOM):	82830 t
Haddock (GB):	250300 t
Yellowtail Flounder (GB):	58800 t
Witch Flounder (GB+GOM):	25248 t
American Plaice (GB+GOM):	28600 t .

The lower F limit for the optimization process is set to 0; the upper F limit (see equation (16)) not to be exceeded during the optimization process are represented by F_{MSY} estimates taken from the 2005 GARM report (NEFSC 2005). These F_{MSY} values are:

Cod (GB):	0.175
Cod (GOM):	0.225
Haddock (GB):	0.263
Yellowtail Flounder (GB):	0.250
Witch Flounder (GB+GOM):	0.230
American Plaice (GB+GOM):	0.166 .

The values assumed for natural mortality M are also taken from the GARM report and are 0.2 for all species/stocks except for witch flounder which is assumed to be 0.15.

The objective function used here maximizes the overall catch at the end of the rebuilding period and is constraint by rebuilding targets in the following manner:

$$
\begin{aligned}
\text{Objection Function} = \text{Total Catch} \quad & - 2.5 \times \max(0, 216780 - SSB_{GB\ Cod}) \\
& - 2.0 \times \max(0, 82830 - SSB_{GOM\ Cod}) \\
& - 3.2 \times \max(0, 250300 - SSB_{Haddock}) \\
& - 3.7 \times \max(0, 58800 - SSB_{Yt\ Fl}) \\
& - 10 \times \max(0, 25248 - SSB_{Wi\ Fl}) \\
& - 2.5 \times \max(0, 28600 - SSB_{Am\ Pl})\ .
\end{aligned}
$$

The six values right after the minus signs are weight factors of the penalty term and chosen in a way that the species specific rebuilding target biomasses will be reached for certain at the end of the rebuilding period. Selecting these values required some prior experimenting.

Our strategy of optimizing the F values is chosen to be in compliance with the NMFS strategy of "constant F values". I.e., per each species we optimized only one F value (instead of a set of yearly values simultanously) and kept this value interannually constant over the entire rebuilding period. The background for this is that

(1) NMFS does not want to control fluctuating F values, but finds it easier to observe and watch one value kept stable over the entire planning horizon

(2) NMFS expects more stable catch values which would be of some advantage for the commercial fishermen as it stabilizes their income.

For all our calculations we used the interactive matrix language SAS/IML (SAS Institute Inc. 1999). We applied the Dual Quasi-Newton Optimization with the Dual Broyden-Fletcher-Goldfarb-Shanno update to our optimization problem in which the gradients are computed by the finite difference method (SAS Institute Inc. 1999). Fig. 5 illustrates the outcome for 3 of the 6 stocks and species, respectively. The three panels display the temporal trajectories for biomass (B, SSB), catch (C), fishing mortality (F, F_{tot}), and recruitment (R) regarding the three cod and haddock stocks. In all cases, the left y axis represents the three biomass and catch related variables (SSB, B, C), the right y axis the two F related variables (F, total F). The two curves for the F variables (F, F_{tot}) are assigned the same symbol (a square) to indicate that these are directly linked to eachother. To distinguish them two different line types were used: a solid line for F_{tot}, a dashed line with short dashes for the estimated/optimized F values. The two dashed lines with no extra symbols are the species related biomass targets ($B_{MSY,}$ long dashes) and the upper F limits (F_{MSY}, short dashes). All other curves and symbols are directly explained by the legends on the bottom of the figure.

Acknowlegements

We would like to acknowlegde the US Groundfish Assessment Review Meeting for their permission to use and cite the groundfish population and fishery data of year 2005 collected by the National Marine Fisheries Service (NMFS) in Woodshole, MA, USA as input for the optimization procedure. We would also like to thank Steve Cadrin for thoroughly discussing the optimization strategy preferred by NMFS with us and the use of tagging data for the incorporation into the matrix of technical interactions (bycatch matrix). We would further thank SMAST for allowing us to use their bycatch data in order to construct some part of the matrix of technical interactions.

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Figure captions

Figure 1: Conventional stock assessment and management procedure.

Figure 2: Simplified catch-effort diagram for deriving MSY related quantities and proxies (MSY = maximum sustainable yield, F_{MSY} = fishing mortality at MSY, B_{MSY} = biomass at MSY, B_{PA} = precautionary approcach reference point for biomass, B_{lim} = limit reference point for biomass).

Figure 3: Graphical presentation of the algorithmic rebuilding philosophy (DAS = days-at-sea).

Figure 4: Layout of the structure of the non-linear optimization algorithm showing the linkages between the various model equations as they appear in the body of the text. The illustration of the layout is based here on a simplified two-species-two-areas example and a 10-years planning horizon for which the objective function is to be optimized.

Figure 5: The three panels display the temporal trajectories for biomass (B, SSB), catch (C), fishing mortality (F, F_{tot}), and recruitment (R) regarding the three cod and haddock stocks. In all cases, the left y axis represents the three biomass and catch related variables (SSB, B, C), the right y axis the two F related variables (F, total F). The two curves for the F variables (F, F_{tot}) are assigned the same symbol (a square) to indicate that these are directly linked to eachother. To distinguish them two different line types were used: a solid line for F_{tot}, a dashed line with short dashes for the estimated/optimized F values. The two dashed lines with no extra symbols are the species related biomass targets ($B_{MSY,}$ long dashes) and the upper F limits (F_{MSY}, short dashes). All other curves and symbols are directly explained by the legends on the bottom of the figure.

Figures

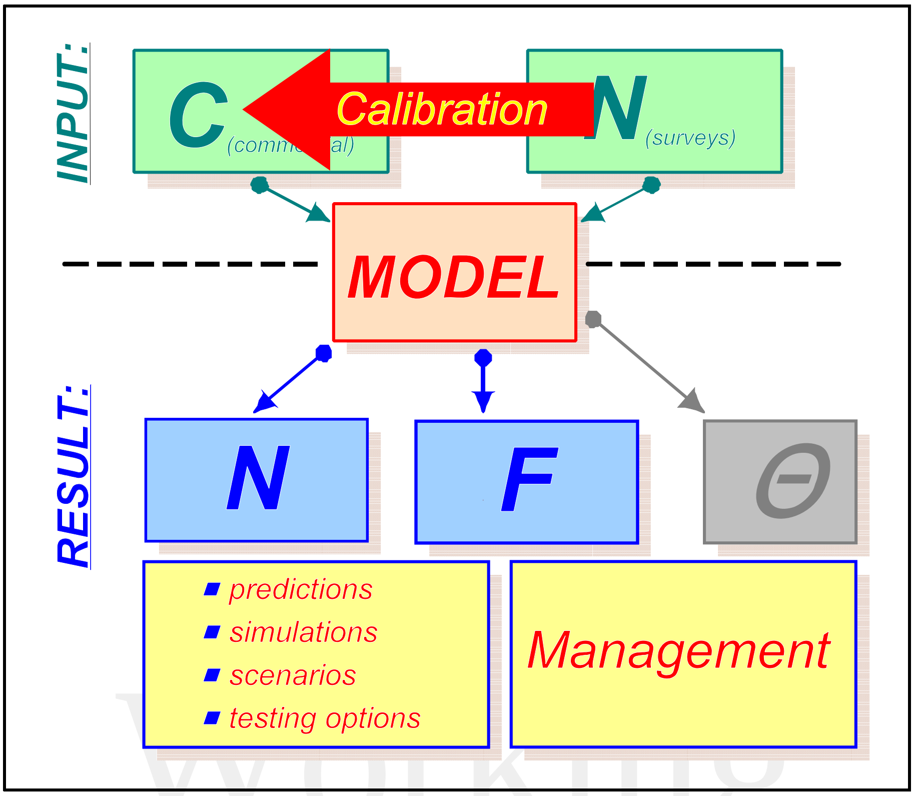


Fig. 1

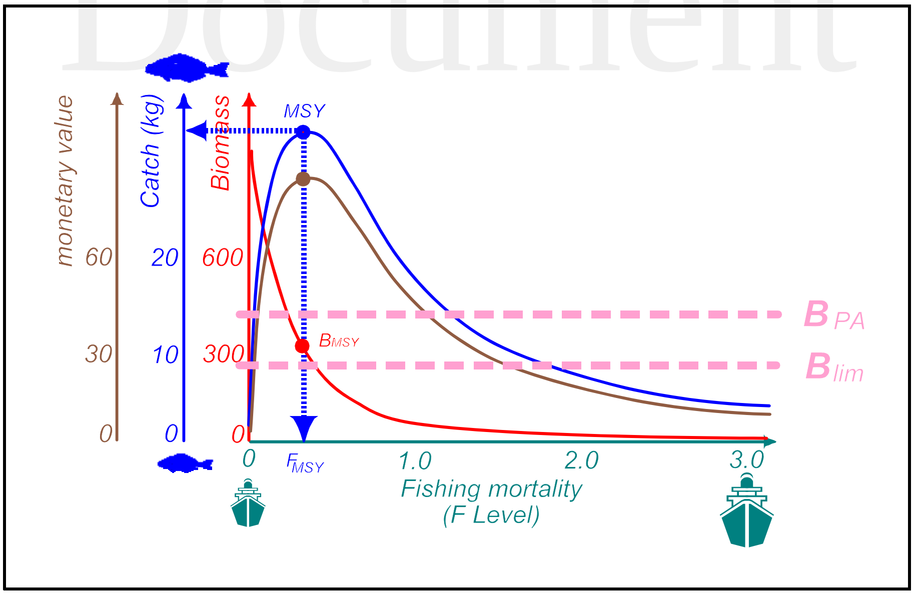


Fig. 2

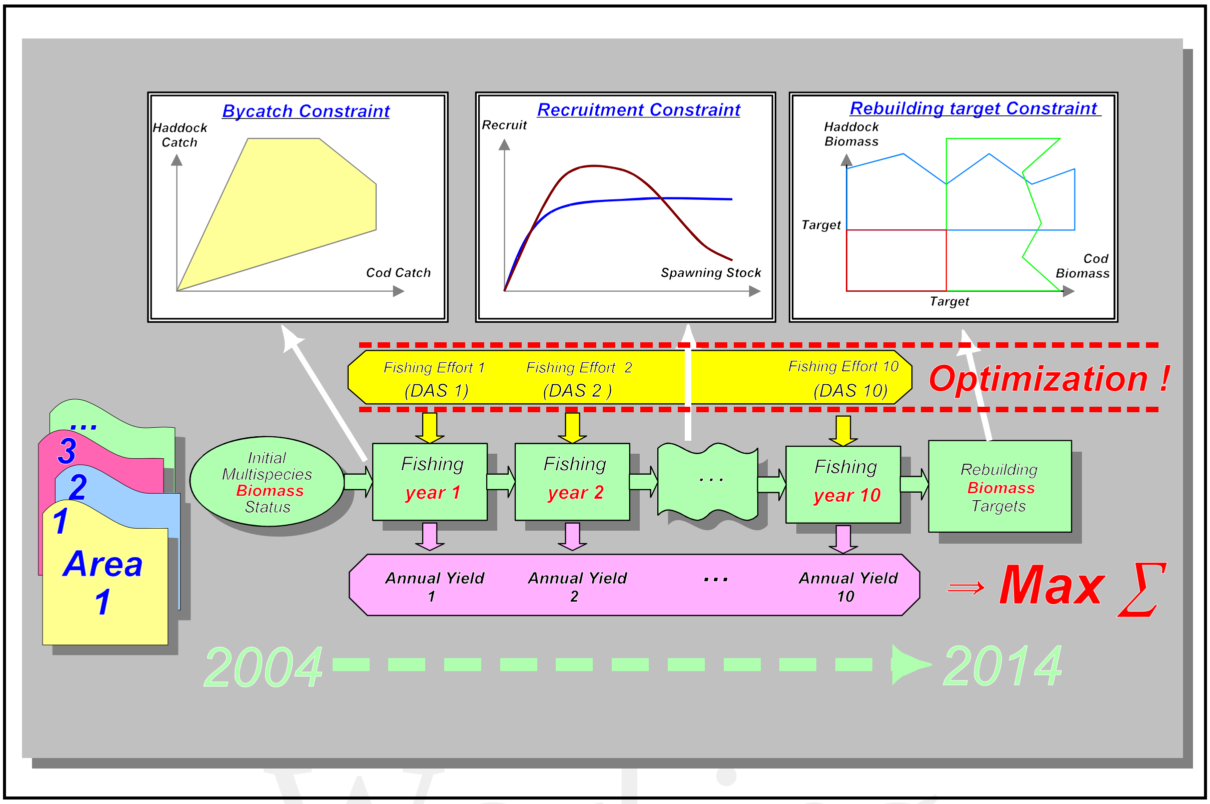

Bycatch Constraint
Haddock Catch
Cod Catch
Recruitment Constraint
Recruit
Spawning Stock
Rebuilding target Constraint
Haddock Biomass
Target
Cod Biomass
Target
Fishing Effort 1 (DAS 1)
Fishing Effort 2 (DAS 2)
Fishing Effort 10 (DAS 10)
Optimization !
...
3
2
1
Area 1
Initial Multispecies Biomass Status
Fishing year 1
Fishing year 2
. . .
Fishing year 10
Rebuilding Biomass Targets
Annual Yield 1
Annual Yield 2
. . .
Annual Yield 10
⇒ Max ∑
2004
2014

Fig. 3

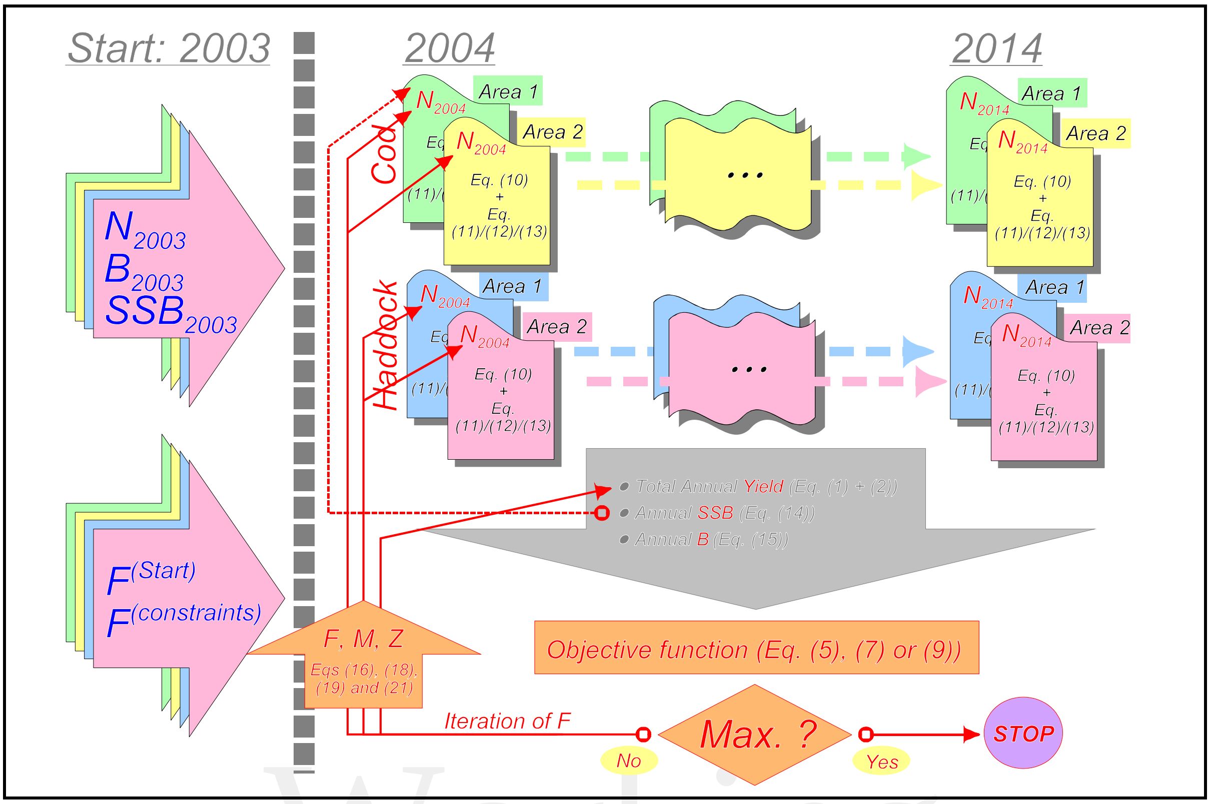
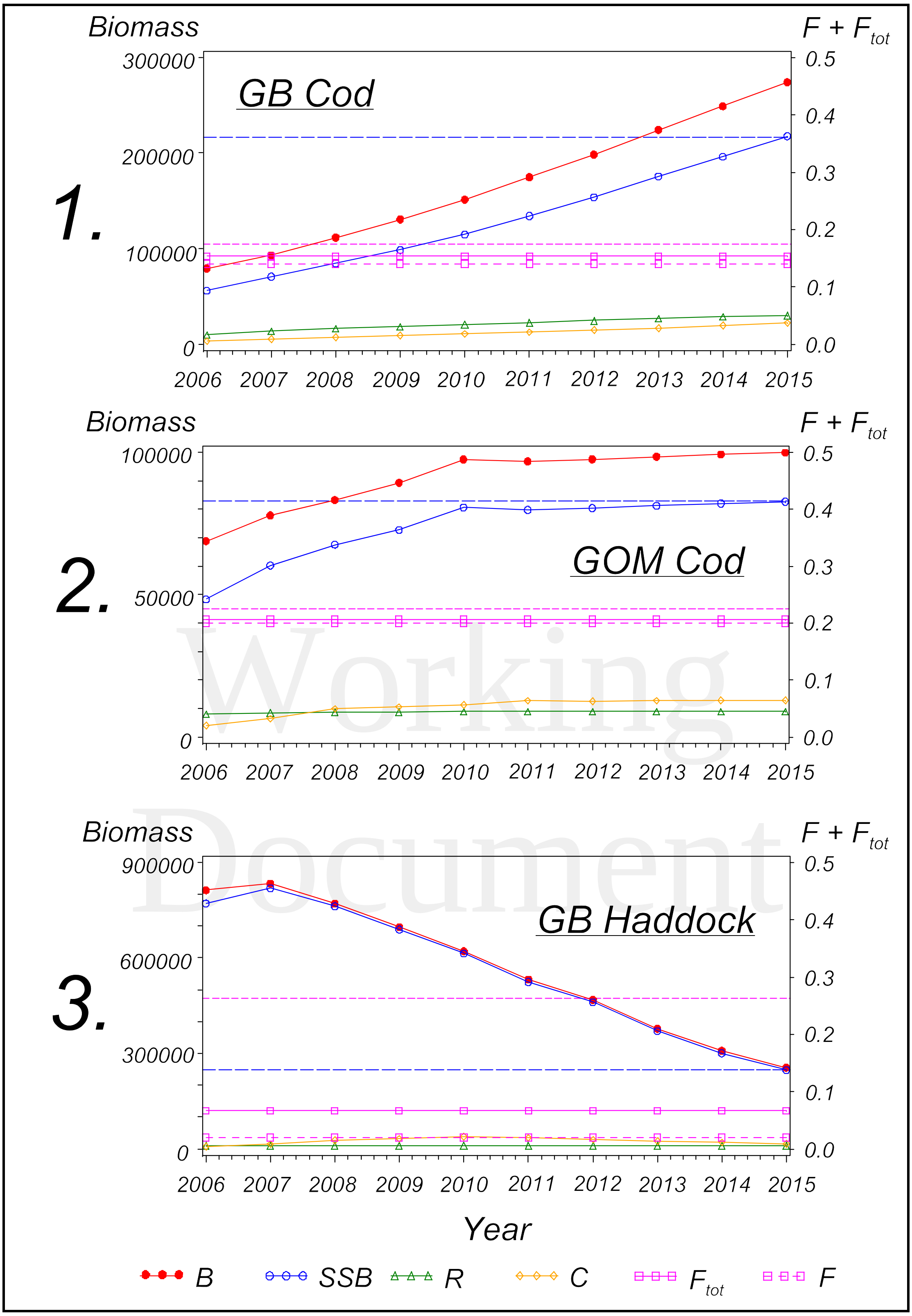

Start: 2003
2004
2014
N2003
B2003
SSB2003
F(Start)
F(constraints)
Cod
Haddock
N2004
Area 1
Area 2
Eq. (10)
+
Eq.
(11)/(12)/(13)
N2014
Total Annual Yield (Eq. (1) + (2))
Annual SSB (Eq. (14))
Annual B (Eq. (15))
F, M, Z
Eqs (16), (18), (19) and (21)
Objective function (Eq. (5), (7) or (9))
Iteration of F
No
Max. ?
Yes
STOP

Fig. 4



Biomass
F + Ftot
300000
200000
100000
0
0.5
0.4
0.3
0.2
0.1
0.0
GB Cod
1.
2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
Biomass
F + Ftot
100000
50000
0
0.5
0.4
0.3
0.2
0.1
0.0
GOM Cod
2.
2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
Biomass
F + Ftot
900000
600000
300000
0
0.5
0.4
0.3
0.2
0.1
0.0
GB Haddock
3.
2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
Year
B
SSB
R
C
Ftot
F

Fig. 5