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Incorporating Uncertainty into Marine Mammal Management

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Abstract.—Management schemes for marine mammals developed by the United States and International Whaling Commission (IWC) have sought to achieve their management objectives by developing control laws designed to calculate acceptable levels of human-caused mortality, while explicitly incorporating some types of uncertainty, and while being robust to other types of uncertainty. The United States developed the "potential biological removal" control law in managing commercial fisheries to reduce incidental catches of marine mammals. The IWC developed, but has not yet used the "catch limit algorithm" control law in managing commercial harvests of baleen whales. In both cases, to develop and test the control law, quantitative management objectives were specified, and only reliably and easily collected data were required. Then, given these specifications and requirements, simulations were used to define the control law and test its robustness to uncertainties in assumptions and data. Finally, to identify unforeseen uncertainties, the management schemes include rules and guidelines on reviews, monitoring programs, and data collection and analyses.

Introduction

Previous marine mammal stock assessments commonly generated a wide range of interpretations about stock status and needed management actions because of limited biological data or, when data were available, large uncertainties in those data. When there were conflicting scientific opinions on stock status, managers often had difficulty in deciding on appropriate management actions, thus, frequently resulting in no management action. The problem was not so much that the scientific process failed, but that the management system had not developed approaches to deal with uncertainties in marine mammal population dynamics data and stock assessment methods.

In this paper, the term "population" refers to a biologically separate group of animals, and "stock" refers to a management unit that may be part of, or all of a population. In theory, the goals of management schemes are to manage populations, so populations were used to develop the control laws. However, in practice, it is only possible to delineate stocks, so stocks are the actual management unit. The term "unknown stock identity" refers to a group of animals that could be part of, one complete, or more than one, population.

In an ideal world, scientists and managers would have information on the following: marine mammal stock structure, distribution, and abundance; natural and human-caused mortality rates; rates, sensitivities, and elasticities of increase; and extinction probabilities. This information would be available for circumstances as they are currently, as they were before any exploitation, and as they would be at maximum net productivity levels. In addition, the scientists and managers would have information on the short- and long-term population and stock effects of present and proposed management actions. For most marine mammals, all or part of this information is missing. In general, available biological data are sparse, and where they do exist, time series are usually short and/or incomplete; consequently, the effects of present and proposed management actions are uncertain.

Because of this background, two management schemes have been developed to manage and conserve marine mammals while explicitly accounting for some uncertainties. The International Whaling Commission (IWC) developed a management scheme for commercial harvesting of baleen whales, with the goal to conserve populations and obtain the highest possible continuing yield. The United States developed a scheme for managing incidental takes of marine mammals in commercial fisheries, with the goal to conserve marine mammal populations and to minimize changes in the fishery. Though the goals differ, a similar approach has been taken toward management. In each management scheme, a management decision rule, or control law, was adopted to determine the allowable harvest or take. Each control law was developed and tested using simulations. Each management scheme includes the chosen control law along with a monitoring program and guidelines on data collection and analyses.

In both cases, risks and benefits of potential control laws were investigated through simulations. The simulations involved the following: 1) specifying quantitative objectives and performance statistics; 2) generating a marine mammal population; 3) removing animals from the simulated population following the control law; 4) using predetermined life history parameters to regulate population growth; 5) sampling the simulated population to estimate abundance and removals; 6) cycling through steps 3–5 over many years; and 7) compiling performance statistics. To determine the effectiveness of a control law through simulation, objectives were compared with performance statistics from many scenarios, each of which differed in its model assumptions and/or in the types and magnitudes of uncertainty typically encountered during assessments. This process resulted in the development of control laws that incorporated some types of uncertainty, were robust toward other types of uncertainty, met management objectives, and used only data that could realistically be collected.

This paper reviews the background, objectives, and development of the IWC and U.S. marine mammal management schemes, with particular emphasis on how uncertainties were incorporated.

IWC Management Scheme

Background and objectives

The IWC is an intergovernmental body established in 1946 under the International Convention for the Regulation of Whaling to provide for the proper conservation of whale populations and make possible the orderly development of the whaling industry. In1975, the IWC adopted the "New Management Procedure" (NMP), the first attempt to manage commercial whaling of baleen whales using a scientific basis, with the goal to ensure sustainability (IWC 1977). The NMP specified that whale populations below their maximum sustainable yield level (MSYL) were to be protected, and catches from other populations would not cause the population to go below their MSYL. Thus, all populations would be managed to be at or above their MSYL. Two supplementary specifications were as follows: 1) populations subjected to stable harvest levels for a considerable period in the past would be allowed to be harvested at those levels in the absence of any definite evidence of decline; and 2) populations not previously subjected to significant exploitation would be limited to a harvest of 5% of the estimated population size.

The NMP ran into difficulties because necessary data were not available. For most stocks, there were no reliable estimates of MSYL relative to current or past abundance, and the relationship between current abundance and MSYL was unknown. When MSYL was estimated, annual updates often led to widely fluctuating catch limits, especially for stocks close to MSYL. In addition, the NMP had no guidelines on how, when, and what kinds of data should be collected, or on how to cope with uncertainties in stock identity, population size, and life history parameters. Moreover, the long-term consequences of the NMP were unknown.

Because of these difficulties, in 1986, the IWC implemented a moratorium on commercial whaling until knowledge of whale populations was improved and a more satisfactory approach to management was developed. As a result, a new management approach, called the "Revised Management Procedure" (RMP), was developed. An essential element of the RMP was the explicit specification of three quantitative objectives, which were agreed upon by all member nations: 1) catch limits should be as stable as possible; 2) catches should not be allowed on populations that are below 54% of their estimated carrying capacity, so that the risk of extirpation of the population is not seriously increased by exploitation; and 3) the highest possible continuing yield should be obtained from a population. The IWC agreed that the second objective had the highest priority. The final version of the RMP was accepted in 1994 (IWC 1994b).

The RMP (Figure 1) includes a catch limit algorithm (CLA) and rules addressing some potential uncertainties and variabilities. The CLA applies to a single stock when stock identity is certain. The rules address uncertainties in stock identity, recent abundance, and stock status, and variability in the sex ratio of the catch.

A "Revised Management Scheme" (RMS), which has not been adopted by the IWC, is designed to ensure that the RMP is implemented as planned (Figure 1). An important issue in implementation is the monitoring of harvests. Ideas proposed for the RMS include national and international observers aboard whaling vessels, DNA profiles of all whales killed, and a vessel monitoring system for satellite tracking of all whaling vessels. Besides monitoring harvests, the proposed RMS might provide data for retrospectively evaluating the efficiency and safety of the RMP, testing assumptions of the robustness trials, improving accuracy of the population models, monitoring the status of harvested stocks, and monitoring the humaneness of the harvest.

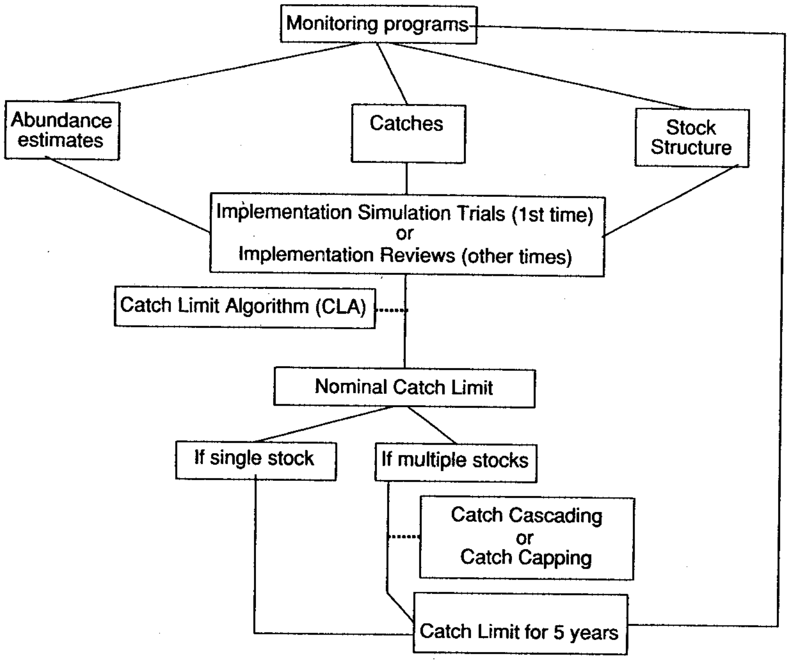


FIGURE 1. Schematic of management scheme proposed by the IWC. Adopted RMP includes items below, and not including, the monitoring programs. Proposed RMS would include RMP, several types of monitoring programs, and perhaps more.

Catch limit algorithm

To account for uncertainties, the IWC designed the CLA to calculate a catch limit, satisfy the three conflicting objectives, and be robust to past, present, and future uncertainties in abundance and harvest estimates, stock identity, and population dynamics. The IWC developed the CLA by examining the performance of five potential catch laws using simulations that cover a wide range of plausible scenarios (Kirkwood 1992).

The basic steps of a simulation were as follows. An initially unexploited whale population was created and historical catches were removed from the population. A full age-structured model governed dynamics of the simulated population and its response to catches. Abundance data were generated to have the same properties as data from abundance sighting surveys. For 100 simulated years, a control law was applied to the population. At the end of 100 years, population status and total catches were determined.

Initially, the control law was subjected to a set of mild tests, called base case trials. If these trials were 'passed', then it was subjected to a set of stronger tests for robustness to departures from assumptions, called robustness trials. Five statistics were used to evaluate performance of the control law: 1) distributions (median, upper, and lower percentiles) of the total catch over 100 years; 2) final population size after 100 years; 3) lowest population size during the 100 years; 4) continuing average catch over the final 10 years (i.e., a surrogate for the realized long-term yield); and 5) inter-annual variability in catch limits.

CLA trials.—Base case trials examined all combinations of the following assumptions in which harvest came from a single population with no uncertainty in stock structure: 1) at the onset of management, the population was either unexploited (i.e., a "development" case), reduced to 30% of its unexploited abundance (i.e., a "rehabilitation" case), or reduced to 60% of its unexploited abundance (i.e., a "sustainable" case); 2) MSY rates (i.e., MSY as a percentage of MSYL) for a population were either 1%, 4%, or 7%, with only the 1% MSY rate being used in the "sustainable" case; 3) abundance survey data were unbiased and available for the first year of management and for every fifth year after that.

Robustness trials investigated the effects on the five statistics when a control law was used in situations where the assumptions were departed from. Initially, the following seven trials were conducted, one at a time: 1) population dynamic parameters varied, with MSYL actually being 40–80% of the estimate, ages at maturity differing due to delayed density dependent effects, carrying capacity showing trends, and the MSY rate showing cyclic changes; 2) initial abundance was different than that examined in base case trials; 3) abundance survey data had upward and downward biases, and were collected at different frequencies; 4) relationships between CPUE data and true abundance differed, including no relationship at all; 5) catch histories prior to the onset of management were uncertain or inaccurate (including underestimation by half), and long periods of protection occurred before management started; 6) carrying capacity fluctuated (including reduction by half); and 7) episodic events (e.g., epidemics) occurred irregularly at which time the population was abruptly halved.

Subsequently, simultaneous departures of multiple assumptions were investigated. Two or more of the following parameters varied: 1) MSY rates, 2) initial depletion levels, 3) periods of protection before management, 4) biased sighting surveys, and 5) biased catch histories (Smith et al., in press). To maximize the power of detecting nonrobustness, a partial factorial design and the same set of random numbers were used to simulate 810 cases of 10 underlying population model scenarios. The performance statistics were the median final depletion and the difference between the 5th and 96th percentiles of the final depletion distribution.

Uncertainty in the relationship between IWC management areas and single biological populations was also a concern to the IWC. To investigate the robustness of a control law to multiple stock situations, the control law was subjected to trials that simulated coastal and pelagic whaling scenarios where stock identity was uncertain.

Coastal whaling trials examined a scenario where whales were taken by a coastal whaling station from a small portion of a management area. The management area was assumed to contain one or two biological populations. If two populations were present, then the boundary between them was assumed to be unknown.

Pelagic whaling trials examined a scenario based on Antarctic whales where the identity of stocks matched a variety of hypotheses, and the MSY rates and initial depletion levels varied. The various stock hypotheses included two stocks being managed as one, one stock being managed as two, stock ranges overlapping or shifting, and stock ranges overlapping and shifting.

CLA specification.—The algorithm that most satisfied all three of the RMP's quantitative objectives in all scenarios was the 'C' procedure; it was chosen as the CLA (IWC 1994a; Cooke 1999). The computer code to implement the 'C' procedure is complex and long; the FORTRAN code is nine pages long (IWC 1994a). As input, the 'C' procedure requires a time series of annual data on catches, absolute abundance estimates for each management area, and the variance–covariance matrix of those absolute abundance estimates. In general, if past catches are large compared with current abundance, then the 'C' procedure calculates a small catch limit, or even no catch. Otherwise, catches are a small fraction of the abundance estimates, typically less than 2%.

The 'C' procedure calculates a catch limit for each management area. Catch limits are based on an assessment where a nonage-structured Pella-Tomlinson type population dynamics model is fit to a time series of absolute abundance estimates using a Bayes-like approach, where at least one abundance estimate exists for an area. If no abundance estimate exists, then the catch limit for that area is zero. The 'C' procedure presumes a wide range of population status could have produced the observed time series of abundance and catches. From a random sample of this range, a distribution of potential catch limits is calculated. To ensure a catch limit certainty to one whale, the final catch limit was defined as approximately the 41st percentile of the distribution. The exact percentile is currently being refined (IWC 2001). By adding data from new abundance surveys (and new catches, if they exist), the distributions of possible population status and catch limit are gradually narrowed down. This generally results in catch limits increasing over time because additional abundance data generally reduce the uncertainty about population status.

CLA constraints.—Cooke (1995) came to three conclusions after the development and testing of the five potential control laws. First, regular direct surveys to estimate absolute abundance were a prerequisite for satisfactory management. Despite considerable efforts, no one was successful in finding a management procedure that worked well without such data. Second, when abundance estimates from regular surveys were available, benefits of other types of data were marginal. The most useful other type of data were total catches. Regular absolute abundance estimates from surveys were, thus, considered both necessary and sufficient for good management. Third, safe management could only be achieved by limiting catches to a small proportion of the absolute abundance. Procedures that allowed higher catches and relied on the detection of trends in abundance did not perform well.

After conducting base case and robustness trials, the IWC Scientific Committee concluded that the most important factor affecting the performance of a control law was stock identity (Cooke 1995). Moderately important factors were bias in abundance and catch estimates, and bias in the variance of these estimates. Least important factors were population dynamic parameters (e.g., age structure, reproduction, density dependence), environmental changes, and sudden events (e.g., epidemics and other mass mortalities).

Stock identity was the most important factor. When stock boundaries were poorly known, depleting or even extirpating a stock was possible even when the total population was not depleted. Uncertainty in stock identity was most critical when populations overlapped on their feeding grounds, and when the extent of the overlap varied between years. This is to some extent an artifact of the performance criteria selected. If the criterion was restated as conserve 'whales,' not conserve 'whale populations,' then stock identity would probably not have been as important.

Bias in abundance estimates was considered as only moderately important because it was not until bias was greater than 50% that the consequences to management became severe. A persistent bias was more serious than a temporary bias that affected only a few estimates. In addition, underestimated variances of abundance were more detrimental than overestimated variances. Cooke (1995) concluded that as survey methods improve, it is more important to use the improved methods to increase precision and decrease bias of current abundance estimates, than to maintain comparability with previous estimates.

Environmental changes and sudden events emerged as least important because catch limits were adjusted with each new abundance estimate, which would reflect effects of such environmental changes and sudden events. In addition, because the catch limit was a small proportion of the abundance estimate, the relative impact of harvesting, as a proportion of the population size, was always small. Even when harvesting in very poor environmental conditions, the impact due solely to harvesting was small, relative to the impact due to the environmental changes and sudden events.

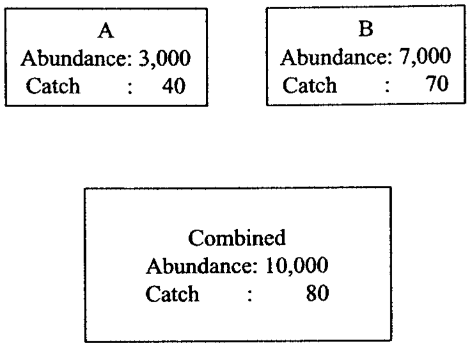
When multiple assumptions were violated simultaneously in single-stock simulation trials, Smith et al. (in press) found that the 'C' procedure was robust, with two exceptions. When severely negatively biased historical catches and low estimated abundance variance were combined, the final whale population was lower than expected. When this scenario was combined with high levels of inter-annual abundance variance, the variability of the final depletion level was unacceptably high. Smith et al. (in press) concluded that because scenarios remain where the CLA may not be robust, and hence not achieve the desired objectives, it is essential that the CLA be tested on each whale stock to which the CLA might be applied.

Rules on uncertainty and variability

As noted earlier, the RMP includes the CLA and the rules addressing some potential uncertainties and variabilities. This section provides details on the rules.

Uncertainty in stock identity.—The rules for addressing uncertainty in stock identity are based on the nature and extent of the area in which the whales are to be harvested. A "Small Area" is defined as an area (possible disjoint areas) small enough to contain whales from only one population, or, if whales from two or more populations are present, then the relative catches from those populations would be in proportion to the relative abundance of the populations. A "Combination Area" is defined as a disjoint union of two or more Small Areas. A "Medium Area" is defined as the area that encompasses all of the known or suspected range of the population(s) of interest, and thus, all of the Small Areas for that population. A "Large Area" is defined as a major ocean area that excludes whales from other population of the same species.

When whales are to be harvested from only a single Small Area, then the calculated (i.e., nominal) catch limit for the Small Area becomes the realized catch limit for that area. When whales are to be harvested from a Combination Area, then the nominal catch limit for the Combination Area may be modified by "catch-cascading," where the nominal catch limit for the Combination Area becomes



Rule	Catch Limit A	B	Combined
Cascading	24=(3000/10000) . 80	56	80
Capping	39=(40/110) . 80	51	80

FIGURE 2. Example illustrating catch-cascading and catch-capping rules to two Small Areas, A and B. Population size for Small Area A is 3,000, and for Small Area B is 7,000. Catch limit for Small Area A is 40 and for Small Area B is 70, when the CLA is applies to each Small Area separately. Catch limit for the combined area is 80, when the CLA is applied to the combined area.

the realized catch limit, but is distributed among the Combination Area's component Small Areas in proportion to the relative abundance estimates of population in the Small Areas (Figure 2). When whales are to be harvested from either a Medium or Large Area, then the nominal catch limit for the Medium or Large Area may be modified by "Catch-capping," where the nominal catch limit of the Medium or Large Area may become the realized catch limit, but is distributed among the Medium or Large Area's component Small Areas in proportion to the relative nominal catch limits for the Small Areas (Figure 2).

If the sum of the nominal catch limits calculated for the Small Areas that make up a larger area (Combination, Medium, or Large Area) exceeds the nominal catch limit calculated for the Combination, Medium, or Large Area, then the realized catch limit in each Small Area is the nominal catch limit from the larger area that is scaled so that the sum of the Small Area catch limits is equal to the nominal catch limit for the Combination, Medium, or Large Area.

Variability in sex ratio of catches.—The CLA was developed without consideration of the sex of harvested whales. When the proportion, P_f of female whales in the catch from the most recent five years exceeds 50% of the catch taken from a Small Area, then the catch limit for that Small Area should be adjusted downwards by the ratio $0.5/P_f$.

This adjustment should be waived if it is agreed that the data from the most recent five year period are too limited to provide a useful indication of the expected sex ratio of future catches.

Uncertainty in recent abundance.—The catch limit for a Small Area is reduced when the time series of absolute abundance estimates used in the CLA does not include an estimate within the past eight years. In each succeeding year beyond eight years in which there is no absolute abundance estimates, the catch limit is reduced by 20% of the unadjusted nominal catch limit. This rule ensures that catch limits are reduced linearly to zero after 13 years without an absolute abundance estimate.

An eight-year period was selected to trigger the phase-out because after about eight years, the population status cannot be predicted reliably. However, the IWC realized that the eight-year criterion was arbitrary because the performance of the CLA did not degrade excessively for intervals longer than eight years.

Uncertainty in stock status.—Before the CLA can be applied to a stock (or stocks), "Implementation Simulation Trials" must be conducted, and after the CLA is applied, "Implementation Reviews" are required. Implementation Simulation Trials involve the delineation of Small Areas and, as appropriate, Medium and Large Areas, as well as the selection of Catch-cascading or Catch-capping, and should consider all available biological, stock identification, and operational data for the particular stock(s) of interest.

Implementation reviews investigate all prior data from the stock(s), and incorporate new data as appropriate to decide if management should be changed; for example, to redefine Small Areas or change the selection of Catch-cascading or Catch-capping. These reviews are scheduled for generally not more than five years after the completion of the previous Implementation Simulation trial or review. Such reviews can be carried out more frequently if new important information becomes available (e.g., new stock structure data).

U.S. Management Scheme

Background and objectives

Under the 1972 U.S. Marine Mammal Protection Act (MMPA), the U.S. National Marine Fisheries Service (NMFS) is responsible for the management and conservation of populations of whales, dolphins, porpoises, seals, sea lions and fur seals that reside in U.S. waters, and the U.S. Fish and Wildlife Service (FWS) is responsible for manatees, walruses, sea otters, polar bears, and dugongs that reside in U.S. waters. The primary objective of the MMPA is to maintain the health and stability of the marine ecosystem by accomplishing the following: 1) maintain a marine mammal population level above its optimum sustainable population (OSP) level, and, at or above the level at which the population ceases to be a significant, functioning element in its ecosystem; 2) restore populations that have been reduced below these levels; 3) approach a zero mortality incidental catch rate of marine mammals by commercial fisheries; and 4) minimize unnecessary disruption of fishing activities. OSP is defined as the number of animals at the maximum net productivity level (MNPL) of the population, keeping in mind the carrying capacity of the habitat and the health of the ecosystem.

After the MMPA was authorized, various attempts were made to define and estimate OSP for cetacean populations (i.e., whales, dolphins, and porpoises). However, just as the IWC could not parameterize the biological models in the NMP due to lack of data, the U.S. scientists could not define and estimate the biological parameter OSP due to lack of data. This failure resulted in an inadequate enforcement of the MMPA. In an attempt to rectify this situation, the U.S. implemented a five-year moratorium on the MMPA's regulations to allow collection of necessary data, and to gain a better understanding of fishery-marine mammal interactions, at the same time that fishing activities continued.

In 1994, amendments to the MMPA defined a more practical management scheme (Figure 3) based on the principle that assessments should precede the use of resources, and that managers should consider the possible consequences of uncertainty, and act accordingly (Mangel et al. 1996). Similar to the IWC's RMS, the MMPA mandates a feedback-loop management scheme. The MMPA management scheme provides checks and balances to address, or at least identify, unforeseen uncertainties, and also address nonscientific issues such as, developing regulations to reduce incidental marine mammal catches in fishing activities to a sustainable level. Specifically, the MMPA management scheme includes the following: 1) periodically assess marine mammal status using the potential biological removal control law, 2) annually review levels of interaction between commercial fisheries and marine mammals, 3) periodically review scientific aspects by independent Scientific Review Groups, and 4) when needed, establish Take Reduction Teams to develop and monitor Take Reduction Plans that reduce fishery incidental catches.

Potential biological removal

Central to this management scheme is marine mammal stock assessment reports. These reports are mandated to contain the following information: descriptions of stock distribution; estimates of abundance, growth rate, and annual human-caused mortality; descriptions of fisheries that interact with the stock; and statements summarizing the status of each stock. Assessments must be updated and reviewed, at least every three years. Assessments of strategic stocks are required to be reviewed annually.

Status is determined by the difference between human-caused mortality levels and potential biological removal (PBR) levels. The PBR level is defined as the maximum number of animals, not including natural mortalities, that may annually be removed from a marine mammal stock, while allowing

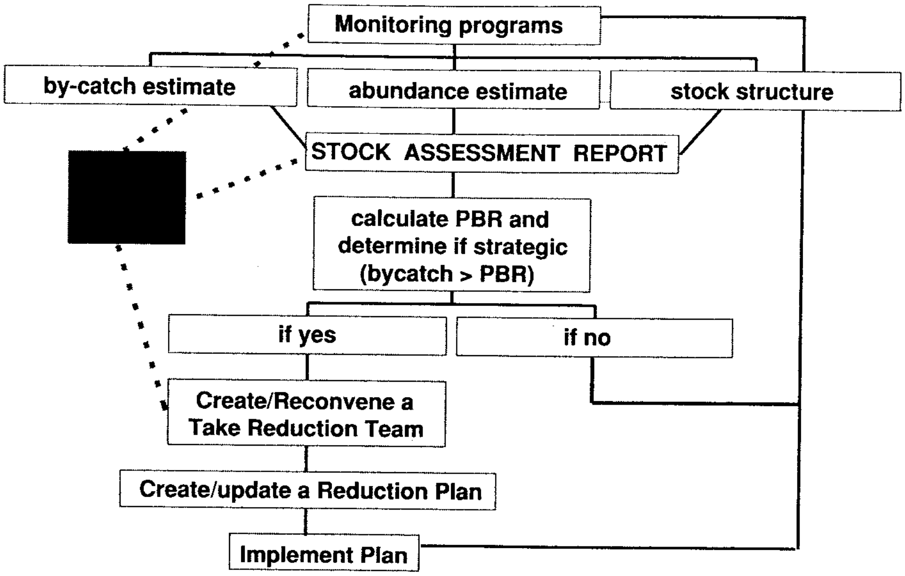


FIGURE 3. Schematic of management scheme mandated by the U.S. Marine Mammal Protection Act (MMPA).

that stock to reach or maintain its OSP level. The PBR is essentially a control law similar to the IWC's CLA. If a stock's human-caused mortality is greater than its PBR, then the stock status is considered 'strategic'. A stock is also considered strategic, if it is listed as threatened or endangered under the Endangered Species Act, as depleted under the MMPA, or is declining, and within the foreseeable future is likely to be listed as a threatened species under the Endangered Species Act.

To achieve the MMPA goal of maintaining populations above OSP, PBR is defined as

$$PBR = N_{\min} \cdot \frac{1}{2} R_{\max} \cdot F_R, \qquad (1)$$

where $N_{\min}$ is the minimum population estimate of the stock, $R_{\max}$ is the maximum theoretical or estimated net productivity rate of the stock when the stock size is small, and F_R is a recovery factor between 0.1 and 1.0. The minimum population estimate is defined as the number of animals in a stock, based on the best available scientific information on abundance, and also on the precision and variability of the abundance estimate. This definition provides a reasonable assurance that the true stock size is equal to or greater than the minimum population estimate. Net productivity rate is defined as the annual per capita net rate of increase in the stock size (i.e., additions due to reproduction, less losses due to mortality). The intent of F_R is to compensate for effects of undefined uncertainties on the recovery of a stock to its OSP level, and to ensure the time to recovery is not significantly increased, especially for stocks listed as endangered, threatened, and depleted.

PBR trials.—To design practical definitions of the three components of PBR, and to ensure management objectives would be met when plausible uncertainties exist, U.S. scientists used simulations of population dynamics and robustness trials (Taylor 1993; Taylor and DeMaster 1993; Wade 1998). This process was accomplished in three steps: define objectives, conduct base case trials, and conduct robustness trials.

The first step was to define quantitative objectives and corresponding performance criteria. Objective one was populations should be maintained above MNPL (50% of carrying capacity (K)). To achieve this objective and to measure long-term performance, $N_{\min}$ was specified such that, if a population started at $N_{\min}$, experienced human-caused mortalities equal to PBR, and F_R equaled to 1.0 for 100 years, then the population size at the end of 100 years was above MNPL, with 95% probability. In addition, to measure short-term performance, $N_{\min}$ was specified such that, if a population started at MNPL, then it was still at or above MNPL after 20 years, with 95% probability.

Objective two was a population should recover to a level close to its carrying capacity, or preexploitation population level (90% of K). To achieve this objective, F_R was defined such that, if a population started at 0.05 K and experienced human-caused mortalities equal to PBR for 200 years, then the population size would equilibrate to a level at about K (0.9 K), with 95% probability.

Objective three was a population, known to be at a low level relative to its preexploitation level (0.05 K), should recover at a rate close to its maximum rate. To achieve this objective, F_R was defined such that, if a population started at 0.05 K and experienced human-caused mortalities equal to PBR, then the time it took to recovery to NMPL (0.5 K) was not delayed by more than 10% (with 95% probability), as compared with the recovery time of a population with no human-caused mortalities.

Step two of the PBR trials was to conduct base case simulations to define $N_{\min}$ and F_R to meet the performance criteria. In these simulation trials, marine mammal population dynamics were modeled with a discrete form of a nonage- or sex-specific generalized logistic equation that incorporated population size, maximum net recruitment rate, preexploitation population size (i.e., carrying capacity), and a shape parameter that controlled the amount of nonlinearity in the density-dependent response of the net recruitment rate.

In each base case simulation trial, carrying capacity was set at 10,000, and MNPL at 0.5 K. The basic steps of a simulation trial were as follows. Starting in year zero, the true population size was estimated using the population dynamics model. Next, starting in year one, for every fourth year, an abundance estimate was randomly chosen, and a new PBR value was estimated. Finally, annual human-caused mortalities, equal to PBR, were subtracted from the current population size. This process was repeated for a specified number of years (20, 100 or 200 years) and final population sizes were recorded. Each trial was repeated 2,000 times, generating a distribution of final population sizes.

Abundance estimates were assumed to have a lognormal distribution, with the mean equal to the true population size, and the coefficient of variation equal to either 0.2 or 0.8. Incidental fisheries mortalities were assumed to have a Gaussian random distribution, with the mean equal to PBR, and the coefficient of variation equal to 0.30.

The first component of PBR, $N_{\min}$, was calculated as the lower percentile of a lognormal distribution:

$$N_{\min} = \frac{N_{\text{best}}}{\exp\left(z\sqrt{\ln\left(1 + \mathrm{CV}(N_{\text{best}})^2\right)}\right)}, \qquad (2)$$

where N_{best} was the best estimate of the current population size, $\mathrm{CV}(N_{\text{best}})$ was the coefficient of variation of N_{best}, and z was the standard normal variate (i.e., equals to 1.96 for the 2.5th percentile, 1.645 for the 5th, 1.282 for the 10th, 0.842 for the 20th, etc.). The choice of z, which affects the level of confidence in $N_{\min}$, was solved to meet objective one.

The second component of PBR, $R_{\max}$, has been directed estimated for only a few marine mammal populations. Survival rates have not been directly estimated because of a lack of biological samples, and a lack of a long series of accurate abundance estimates. Accordingly, plausible default values for R_{max} were defined by examining all available data from all stocks (Wade 1998). The default values were set to 0.04 for cetaceans, and 0.12 for pinnipeds. In base case simulations, the value of the true $R_{\max}$ used in the population dynamics model was defined as the $R_{\max}$ used in the PBR calculation.

The third component of PBR, F_R, was initially assumed to be unity when solving for z in $N_{\min}$. Subsequently, F_R was solved to meet objectives two and three.

Step three in the PBR trials was to conduct robustness trials to evaluate if the definitions defined in the base case trials (step two) were still adequate when assumptions were relaxed and plausible uncertainties were included. Eight robustness trials were conducted (Wade 1998): 1) estimated human-caused mortality was equal to 1/2 actual human-caused mortality; 2) estimated abundance was twice actual abundance; 3) estimated $R_{\max}$ was twice actual $R_{\max}$; 4) estimated CV of abundance was less than the actual CV (estimated CV of 0.2 when actually 0.8 and estimated CV of 0.8 when actually 1.6); 5) estimated CV of human-caused mortality was 1/4 actual CV; 6) abundance surveys were conducted every 8 years, instead of the default 4 years; 7) MNPL was set to 0.45 K, rather than the assumed 0.5 K; and 8) bias was added to the human-caused mortality estimate, and MNPL was equal to 0.7 K.

These trials were considered to represent plausible 'worst-case scenarios'. Trial six was later expanded to find the optimum time interval between abundance surveys, given a range of precision in the abundance and human-caused mortality estimates (Wade and DeMaster 1999).

PBR specifications.—After conducting the base case and robustness trials, the MMPA objectives were met by defining the components of PBR as following (Wade 1998):

$N_{\min}$ = 1) the 20th percentile of a lognormal distribution of the abundance estimate (which is equivalent to the lower limit of a 60% 2-tailed confidence interval), or 2) a direct count of animals, such as a count of hauled-out seals.

$R_{\max}$ =1) 0.04 for cetaceans, and 0.12 for pinnipeds and sea otters (default values), or 2) a reliable stock specific estimate from a peer-reviewed journal, or from a review group, such as a Scientific Review Group or the Scientific Committee of the IWC.

$F_R = 0.1$ for stocks listed as endangered, and 0.5 for stocks listed as depleted, threatened, or of unknown status (default values). The value of F_R should be adjusted depending on the coefficient of variation of the mortality estimate (discussed later).

Guidelines on uncertainty and variability

To account for other types of uncertainty and to maintain quality data, additional guidelines were developed (Barlow et al. 1995; Wade and Angliss 1997). These guidelines are discussed below.

Uncertainty in abundance estimates.—Because only one value for $N_{\min}$ is required to calculate PBR, information from a time series of abundance estimates would be underutilized if previous abundance estimates were ignored. To use time series information, and to decrease uncertainty in the current abundance estimate, three guidelines were developed.

The first guideline is if appropriate, a weighted average of abundance estimates from an eight-year period should be used for N_{best}, where the weight for each abundance estimate is its variance. This guideline is considered appropriate when there are no obvious trends in abundance, estimates are for the same region, and other known factors have not drastically affected the status of the stock.

The second guideline is if a stock is declining, then F_R should be reduced. The value of F_R should account for the magnitude and duration of the decline, although no specific guidelines have been provided.

The third guideline is, if the current abundance estimate is nine years or older, then PBR should be considered unknown, not zero. In these circumstances, a decision on the stock status should be made on a case-by-case basis.

Uncertainty in incidental catch estimates.—Because only one value of the human-caused mortality estimate is required to be compared with PBR, information from a time series of estimated human-caused mortalities would be underutilized. To use time series information, and account for uncertainties in the mortality estimates, two guidelines were developed.

The first guideline is, if appropriate, a five-year unweighted average of annual mortality estimate should be calculated. This is considered appropriate if the fishery has not changed significantly within the five-year period.

The second guideline is, when the coefficient of variation (CV) of the mortality estimate is high (>0.3), F_R should be reduced. The value of F_R should be 0.48 when the CV of the mortality estimate is 0.3–0.6; 0.45 when the CV is 0.6–0.8; and 0.40 when the CV is greater than 0.8. The reduced value of F_R is necessary because F_R was defined in the simulations when the CV of estimated mortalities was assumed to be less than or equal to 0.3.

Uncertainty in sex composition of human-caused mortalities.—In situations where human-caused mortalities are predominately (>50%) females, F_R should be reduced to compensate for the greater impact of this mortality on the stock. However, the guidelines have not specified how large the reduction should be.

Uncertainty in other factors.—The intent of the recovery factor is to compensate for uncertainties not accounted for in other components of PBR. This provides flexibility to appropriately adjust the recovery factor to meet MMPA objectives. For example, if human-caused mortality estimates are unbiased because of high observer coverage, then it may be appropriate to increase the recovery factor to reflect this greater certainty. However, no specific guidelines exist on the appropriate value of F_R. For stocks of unknown status, recovery factors of one are suggested to be reserved for cases where estimates of $N_{\min}$, $R_{\max}$, and human-caused mortality are all unbiased, and where stock identity is unequivocal.

Uncertainty in stock identity.—Stock identity for most marine mammals in U.S. waters is uncertain. The robustness trials did not explicitly include uncertainty in stock identity or multi-stock scenarios. To address potential problems due to uncertain stock identity, a general guideline is: "For the purposes of management under the MMPA, a stock is recognized as being a management unit that identifies a demographically isolated biological population. In the absence of adequate information on stock structure and fisheries mortality, a species' range within an ocean should be divided into stocks that represent defensible management units. . ."

Classifying interactions between fisheries and marine mammals

The MMPA mandates annual classification of all U.S. commercial fisheries into category I, II or III, based on whether the fishery has a frequent, occasional, or remote likelihood, respectively, of marine mammal incidental mortality and serious injury. Categorization is built on a two-tiered, stock-specific approach that first addresses the total impact of all fisheries on each marine mammal stock, and then addresses the impact of individual fisheries on each stock. The tiers are:

Tier 1: If total annual mortality and serious injury across all fisheries that interact with a stock is less than or equal to 10% of PBR for the stock, then all fisheries interacting with this stock should be placed in Category III. Otherwise, the fisheries should be subject to Tier 2 classification rules.
Tier 2—Category I: Annual mortality and serious injury of a stock in a given fishery is greater than or equal to 50% of the PBR level.
Tier 2—Category II: Annual mortality and serious injury in a given fishery is greater than 1% and less than 50% of the PBR level.
Tier 2—Category III: Annual mortality and serious injury in a given fishery is less than or equal to 1% of the PBR level.

The MMPA mandates that vessels in fisheries with frequent or occasional marine mammal incidental mortality and serious injury levels (Categories I or II) must register, and must carry an observer, if requested by NMFS. Observers collect data used to estimate total incidental catch, update the classification of the fishery, and design/monitor a Take Reduction Plan.

Independent scientific reviews

The MMPA mandates the establishment of three independent regional Scientific Review groups representing Alaska, the Pacific Coast (including Hawaii), and the Atlantic Coast (including the Gulf of Mexico). These groups periodically review scientific aspects. Responsibilities for these groups include: providing advice on stock assessment reports and methods to reduce incidental catches in fishing operations; identifying uncertainties and research needs; and making recommendations on scientific issues.

Regulations to reduce incidental catches

When a stock is classified as strategic because fishery-caused mortality estimates are greater than PBR, the MMPA mandates a Take Reduction team be established to prepare a draft Take Reduction plan. The Team is composed of experts in marine mammal biology, fishery practices, management, and conservation of marine mammals. Membership may include representatives of all stakeholders, such as representatives from state and federal agencies, regional fishery management councils, interstate fisheries commissions, academic and scientific organizations, environmental groups, fishery groups that incidentally catch the stock, Alaska native organizations, and Indian tribal organizations.

Ideally, the team develops a Take Reduction plan that is a consensus agreement. However, even if the plan is not a consensus, NMFS must publish in the *U.S. Federal Register* a plan that reduces fishery-caused mortality to a level below PBR, and a discussion on the differences between the published plan and the plan developed by the team. Following public review and comments, a final plan is published and implemented. After that, the team(s) that developed the plan periodically meets to monitor the success of the plan and recommend modifications, if needed.

Comparison of the Two Management Schemes

In the past, scientists and managers managed marine mammal stocks using detailed biological assessments. The IWC implemented the NMP, which depended on estimating parameters in detailed biological models, and the United States implemented the 1972 version of the MMPA, which depended on estimating the biological parameter OSP. These attempts were not successful because for most stocks, the necessary data to estimate the biological parameters were not available. For stocks where assessments were completed, a wide range of opinions often ensued concerning the interpretation of the assessments and the need for management measures. As a result, in some cases, no management actions were taken. In other cases, such as those dealt with by the IWC, large inter-annual changes in the allowable catch were calculated. And, in other cases where management actions were taken, long-term consequences of the management actions were unknown.

Because of this history, both the IWC and United States undertook another approach to define their management schemes. These approaches included specifying quantitative objectives and performance statistics; conducting simulations to define and test control laws, using only data and types of uncertainties that were reliably collected; investigating the robustness of control laws to different types of uncertainties; determining long-term effects of the control law; periodically reviewing and updating data to monitor control law performance and identify uncertainties (a feedback-loop management scheme); and, finally, developing guidelines for data collection and analysis methods.

There are numerous advantages to the simulation approach. Simulations allow many tests to be conducted quickly, and long-term consequences of control laws to be evaluated. To determine precisely how a control law is performing, the status of a simulated population can, after any time period, be precisely determined (Cooke 1999). In addition, and most importantly to the marine mammal populations, extinction of a simulated population is of no consequence. Disadvantages of the simulation approach are objectives, plausible parameter estimates, scenarios to test, and performance statistics should represent reality, and should be agreed upon by all stakeholders. In addition, interpretation of results may be difficult, especially, when there are conflicting objectives.

The feedback-loop strategy is used at two levels in both the IWC and U.S. management schemes. On one level, within the control law, new data can be incorporated to reduce the uncertainty in the catch limits. On another level, within the management scheme, a system of checks and balances to identify unforeseen uncertainties include periodically reviewing the assessment, collecting data other than that required by the control law, monitoring catches, and educating the parties catching the marine mammals.

Both management schemes require only periodically collecting new data. This allows data collection to be logistically, and economically feasible. Simulations were used to determine the most appropriate schedule for data collection. It was found that annual updates were not necessary, updates every four or five years were sufficient.

Both management schemes also contain guidelines on data collection and analyses. These guidelines are expected to evolve as methods are improved, and new questions and uncertainties are encountered.

The general approach of incorporating uncertainties via simulations was similar in both cases. However, the approach taken by the IWC was more comparative and comprehensive. The IWC developed and compared five control laws that used different input data and algorithms to calculate a catch limit. This comparison allowed the IWC to define appropriate input data and methods to incorporate some types of uncertainties, and yet still satisfy management objectives. Concerns were raised that the assumptions made within the simulation model dictated the success of a control law. To address these concerns, hundreds of base case and robustness trials were conducted, which modified model assumptions, and incorporated many different scenarios. Developers of the MMPA did not use such an exhaustive approach, perhaps because the IWC results were already available, and the IWC's conclusions could be adapted without repeating all the work.

Both schemes incorporate some types of uncertainty into the control law, and other types into associated rules and guidelines, though details differed. One obvious difference between the control laws developed by the IWC and the United States is the level of complexity, as illustrated by comparing the length of the IWC's CLA (nine pages of FORTRAN code) to the MMPA's PBR (equations 1 and 2). The PBR equation is easy to understand, while the CLA's algorithm is not. The CLA is complex because it is designed to use information from a series of abundance and catch estimates, and to explicitly incorporate the uncertainties of these estimates. Thus, as the time series grows, catch limits became more precise. This is because, as the time series grows, the stock status is known more precisely; and thus, the catch limit is also known more precisely. The PBR equation does not explicitly use information and uncertainty from a series of abundance and mortality estimates. However, because time series of marine mammals in U.S. waters are now becoming sufficiently lengthy, guidelines were developed to utilize this information.

Uncertainty in stock structure is handled differently within the two schemes. The most important factor affecting performance of the IWC's CLA is stock identity (Cooke 1995). Because of this, many multispecies robustness trials were conducted, and complex rules were developed to allocate catch limits in such way to compensate for potential unknown multispecies relationships. This level of testing was not conducted for PBR, and rules regarding multi-stocks were not specified in the MMPA guidelines.

The IWC and MMPA control laws also differed with respect to flexibility. The CLA is rigid, and like a black-box, when abundance and catch data of baleen whales are entered, a catch limit is outputted. The IWC does not recommend the CLA algorithm be redefined or modified. This is deemed not necessary because the CLA was demonstrated to be robust to many types of uncertainties. The MMPA does not follow this philosophy. The MMPA is specifically written to allow values of any or all of the three components of PBR to be changed, if scientifically justifiable. This flexibility appears to be necessary for two reasons. One, PBR was not exhaustively tested for robustness to many types, and combinations of uncertainties and invalid assumptions; thus flexibility may be needed in some specific cases. And, two, perhaps more importantly, PBR must be applied to all stocks of whales, dolphins, porpoises, seals, sea lions, sea otters, polar bears, and manatees that reside in U.S. waters. It does not seem possible for all those species to be managed safely by one rigid control law, especially without more extensive testing.

Conclusion

Using simulations to develop and test control laws to estimate catch limits appears to be an appropriate approach to incorporate some types of uncertainty, and determine robustness to other types of uncertainty. Moreover, to account for known uncertainties not already addressed, the IWC and MMPA management schemes include guidelines and rules on data collection and analyses, and to identify unforeseen uncertainties, the management schemes include periodic reviews and monitoring plans.

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