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FROM THE GOLDEN AGE TO THE NEW INDUSTRIAL AGE: FISHERY MODELING IN THE EARLY 21ST CENTURY

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ABSTRACT. If the Golden Age of fishery modeling is over, the New Industrial Age is beginning. In this new age (the early decades of the 21st century), we[1] expect to see increasing use of high-level modeling tools, assessments closely tailored to each stock and its data, more multi-agency collaboration, wider use of multiple-model assessments, and extensive peer review of stock assessments. We hope that fishery management, as well, will be seen as a proper object of peer review, from which it should benefit substantially. We believe that increasing attention will be paid to financial efficiency, both in shaping data collection programs and in specifying what information must be modeled to effect management. If presently depleted stocks start to recover, analysts will be required to examine in more detail the dynamics of increasing stocks. That would constitute a pleasant duty, and one that may yield new insights in population biology.

KEY WORDS: Resource management, stock assessment, population modeling, peer review, fishery management, performance measures.

1. Introduction. The past few decades, considered the Golden Age of fishery modeling by Quinn [2003], have seen extensive progress in the field. Scarcely 40 years ago, yield-per-recruit analysis, as introduced by Beverton and Holt [1957], and stock-recruit analysis, as introduced by Ricker [1954], were novel and technically advanced. Today, models have become more complex (e.g., Hampton and Fournier [2001]), and it is not unusual to estimate growth, recruitment and optimal yield simultaneously with stock status. Indeed, in many fisheries today, the potential for model complexity has outstripped the data available for parameter estimation.

Thus, the contemporary fishery modeler faces the paradox of having sophisticated biostatistical modeling tools, but lacking sufficient biological information to apply them conclusively. In some fisheries, data collection is extensive because of the value and nature of the resources. For example, the Pacific yellowfin tuna and Bering Sea walleye pollock fisheries are sampled intensively, and they make use of complex assessment models with 2,742 and 723 parameters, respectively (Ianelli et al. [2001], Maunder and Watters [2001]). The economic value of those fisheries supports extensive data-collection programs, and the concentrated nature of the fleets makes excellent data collection practical.

However, complete, accurate data on a stock and its fisheries are far from typical. Worldwide, most harvested stocks of fish are much less valuable than the two mentioned, and data collection is often far from complete. For example, it is inconceivable that the diverse and scattered southeastern U.S. fisheries on reef-associated fishes will ever attain such sampling intensity. These semi-artisanal southeastern fisheries—and many others worldwide—will likely fall into the situation described by Ludwig and Walters [1985]: "Because of large costs of obtaining information about fish stocks, we suspect that management strategies in fisheries will always be developed in a twilight zone of inadequate information." In the upcoming New Industrial Age of fishery modeling, that situation will provide many opportunities for research, both into modeling methods themselves and into their best application in resource management.

The New Industrial Age (as we call our vision of the next few decades) will be a time in which model developments from the Golden Age will be used intensively and put to the test. Here, we put forth our vision of how this paradigm might occur, particularly in the United States. We also suggest areas that we think will be particularly important for research. As in the Industrial Revolution, powerful tools (now, electronic ones) will make formerly impossible tasks almost routine. The use of computer-intensive methods, introduced during the Golden Age, will be even more important in the New Industrial Age, to allow freedom from distributional assumptions and ease of calculation (Efron and Tibshirani [1991]). Also, high-level programming toolkits and languages will continue their increased use in fishery modeling.

Methods for collecting fish and fisheries data around the world are very diverse. Since model and data are closely linked, mass replication of a standardized product will not be the rule in the New Industrial Age, as it was in the Industrial Revolution. Instead, analysts will use powerful computational tools to implement model variants developed for the stock under consideration. Simulation studies of accuracy, bias and robustness, and use of multi-model assessments, will be used increasingly (Butterworth et al. [1997]). Sampling efficiency, in both statistical and economic senses, will be an important topic of investigation and concern. Retrospective analyses of successes and failures of fishery modeling and management will provide valuable information on better strategies for data collection, assessment and management. Management of fisheries on diverse social criteria will continue, requiring fishery modelers to incorporate social, economic and ecosystem components into assessment models. In general, then, we envision wider and more technical use of existing methods, rather than conceptual breakthroughs, in the New Industrial Age. Here we discuss in more detail some predictions and suggestions for future research in fishery modeling and management.

2. Performance of fishery management. Many simulation studies have been conducted to examine properties of assessment models, and peer review of stock assessments has become common. However, fewer studies and reviews have examined performance of fishery management as it is—and might be—practiced. Several areas require investigation to provide a better view of the historical and potential performance of marine fishery management. A first question in this realm is to what degree managers have adopted the scientific advice offered to them. Any judgment on whether fishery science and modeling have been useful in managing fish stocks as renewable resources depends on knowing the extent to which the findings of fishery science have actually been used by managers (Ludwig et al. [1993], Rosenberg et al. [1993]). Both longitudinal studies (comparing management of a single stock or by a single management body over time) and latitudinal studies (comparing management among stocks or among management bodies) would be of interest, as would be studies comparing expected benefits from fisheries that took scientific advice into account to differing degrees.

A second question in this general area is whether realized fishing mortality rates have been identical to those prescribed by regulation. The answer to that question is of particular importance in setting new management targets. If it is known a priori that targets are likely to be overrun, the argument can be made that future targets should be reduced to account for the expected discrepancy. In setting targets for catch or fishing mortality rate, it is mathematically trivial to adjust the management targets to account for expected bias (e.g., Prager et al. [2003]). A sensible approach to making such adjustments might use a sliding window of recent years to estimate past bias in implementation of management measures. Then, implementation in a future period would be assumed to be biased (i.e., result in overruns) to the same degree as management in recent years. Such a procedure would incorporate into management knowledge about bias in recent implementation and would also give an incentive to improve control, whether through stronger enforcement or other measures, because management targets in the future would increase as the average of recent overruns declined. Though mathematically logical, such a policy might prove unpopular and thus difficult to implement. Studies from a variety of perspectives, both comparative and theoretical, would be of interest.

A third area of needed management research springs from the everyday observation that scientific advice on fisheries is uncertain. That fact has been used to argue for lack of management (Weber [2001]), but with the declines of fisheries worldwide (e.g., Myers and Worm [2003]), that argument seems less compelling. A more balanced response to recognizing uncertainty is selection of management strategies robust to uncertain assessment results (e.g., Ludwig et al. [1993], Ludwig [2002]). More research is needed into the properties of current management strategies in the presence of uncertainty and into management strategies that are robust to uncertainty. Uncertainty in this context includes uncertainty in the assessment advice itself, in effective implementation of control measures, in side effects (e.g., mortalities of released or discarded fish) of management, and stochasticity in population processes (growth, recruitment) in a varying environment. If such research were to identify better management techniques, or even were to provide more definite evidence to prefer some current management techniques over others, it could be of central importance to our field.

3. Use of relative and dimensionless measures. How much information is really needed to manage fisheries? As indicated by the title of Smith's [1994] book, *Scaling Fisheries*, much energy and scientific work in fishery research has been spent on scaling fisheries to absolute biomass. That amount of effort expended is not surprising, as relating trends in relative biomass to the precise absolute biomass of a natural population is an extremely difficult task. It seems possible, though, that effective fishery management could proceed without precise scaling and, if so, management could be less costly and more effective. A related, but distinct, line of thought has been explored by Walters and Martell [2002]. The use of relative measures of biomass and fishing mortality rates in fishery assessments has increased in recent years. It has been shown that such measures, when used to describe production-model results, are considerably more precise than the scaled results (Prager [1994]). It has not been shown, however, whether such results also apply to age-structured assessment models. We suspect that they do, because in both types of models the estimated catchability coefficient q relating absolute to relative biomass is a major area of uncertainty, but simulation studies would help to clarify that point.

If relative measures are sufficient for fishery management, at least of some stocks, we envision that reference points used in management could be defined in conceptual terms, i.e., in terms of specific benchmarks, rather than their estimates or other specific numerical values. (This is done to some degree in U.S. fishery management now, but apparently there may be legal hurdles to including such concepts in fishery management plans.) Assessments would then concentrate on estimating status of the stock and fishery on a dimensionless scale relative to corresponding limit or target reference points (e.g., B/B_{MSY} and F/F_{MSY}), rather than in terms of absolute biomass B or (equivalently) absolute fishing mortality rate F. Of course, knowledge of absolute biomass can be useful, but it may be prohibitively expensive to obtain. It seems to us that such absolute knowledge is usually of secondary, not primary, importance in rational management of fishery resources.

4. Multi-model assessments and multi-faceted models. Contemporary weather forecasts are often made by averaging results of several models (Krishnamurti et al. [1999]). We envision that in the coming decades, fishery assessments will routinely use not just one model but a spectrum of models (Patterson [1999]). Although the results may not be averaged, an assessment based on a single view (model) of the stock might be considered incomplete and less certain. When an assessment uses more than one model, disagreement of models becomes a warning sign that can indicate model or data failure, or even errors in implementing one or more of the models. We hope that the value of applying multiple models will become recognized and that the multi-faceted view of a stock will be taken for granted in the coming decades. Today's models have become more sophisticated, and they incorporate more sources of information and more aspects of life history. For example, some contemporary catch-at-age models incorporate an internal recruitment function. Any such model describes a self-sustaining population, and in that sense it combines features of production models and classic catch-at-age models. We anticipate that the trend towards greater complexity will continue. Its limitation is that as models become more complex, more data or assumptions are needed to arrive at repeatable conclusions (Schnute and Richards [2001]). A side effect of increased complexity is that it reduces the ease and speed with which sensitivity analyses, stock projections and simulations of management actions can be performed.

To provide a framework for balancing simplicity and completeness, research is needed on methods to determine optimal complexity in modeling a given situation. Because statistical criteria based on goodness of fit can perform poorly when used on long-tailed fishery data (e.g., Prager [2002]), a different approach seems necessary. The ultimate limit on model complexity may be set by limitations on what can be communicated convincingly to managers, fishermen and the public.

5. Collaboration and peer review. We foresee increased use of collaborative assessments in the coming decades. By that, we mean assessments in which scientists from several agencies, or even several nations, contribute data and analyses. Increased collaboration will occur for two basic reasons. The first is that assessment science has become more complex and specialized. It is not common that an expert on a species' natural history will have sufficient modeling expertise to conduct a state-of-the-art assessment, and it is equally unlikely that the assessment scientist will have complete knowledge of stock biology, fishery operations and corresponding data collection programs. Because both analytical and observational knowledge are needed for a proper assessment, there is a clear need for scientific collaboration in assessments. Our experience with collaborative assessments in the southeastern U.S. and international fora also indicates that use of a collaborative process can provide rapid progress towards higher-quality assessments. The participation of numerous specialists ensures that the many assumptions made in the course of a stock assessment are as sensible as possible and that deficiencies in stock knowledge are identified and resolved by the relevant experts. Questionable assumptions are identified during the assessment process, not in later reviews.

There is a second, not wholly scientific, reason that collaboration in assessments should and will increase. We live in a time of over-exploitation of the world's fisheries and thus more restrictions on fishing, which are unpopular. A collaborative model of assessments relieves any single scientist or agency from being the sole messenger for unwelcome scientific findings. Assessment results, particularly when they signal restrictions to come, may be more readily accepted and defended when they are consensus views of specialists from varied geographic and political areas.

A related phenomenon is the increase in peer review of stock assessments. It is related because not only scientific, but also political, considerations are behind its increased use. It is also related because collaborative assessments have every chance of being stronger when reviewed, having stood the scrutiny of many viewpoints in the assessment process itself. As implied above, we believe that fishery management is an equally valid object of peer review. Standards for judging management effectiveness will not be the same as those used for scientific work. Nonetheless, the same type of independent review that has led to remarkable progress in science should be capable of improving fishery management, as well.

Some review of stock assessments wind up as alternative assessments by the review panel itself, as in National Research Council [1994]. The tendency for this to occur is strong, because expert reviewers are usually expert assessment scientists, and many are more drawn to doing than to reviewing. However, that pattern was criticized by NRC [2002], which pointed out that when it occurs, the transparency and openness of the review process are spoiled. We agree. When a review panel changes the assessment under review for their own, the public gets an unreviewed assessment, done by the review panel, and the peer-review process is vitiated. A side effect is that when assessment personnel know that their efforts will be redone by a review panel, they may be less inclined to produce their best work. We believe that assessment and review must be kept separate, just as they are in refereed scientific publication. The function of reviewers is to judge the adequacy and quality of an assessment, given the inevitable limitations of resources. If the assessment is inadequate, it must be redone—by the assessment staff, not the reviewers. An unresolved procedural question is under what circumstances such revisions should require further review.

6. Appropriate tools for assessment models. The past two decades have seen computer spreadsheet programs, originally designed for budget analyses by accountants, become popular tools in fishery science. Indeed, several recent fishery texts devote considerable space to use of spreadsheets (Punt and Hilborn [1996], Haddon [2001]). Spreadsheets are flexible tools for prototyping analyses, and their integrated graphics are convenient, if unrefined. Spreadsheets' presentation of immediate results can aid learning and debugging. However, despite their remarkable flexibility and ease of use, spreadsheets can be prone to programming errors and their code is difficult to document, review and maintain. These flaws occur primarily because the user's programming code is mostly hidden and generally not available as a readable program, nor do spreadsheets use typical programming loop structures for repeated calculations (Prager and Mohr [2001]). Some spreadsheet statistical algorithms have been found inaccurate (Knusel [1998], McCullough and Wilson [1999]). While that could occur in libraries for any programming tool, it seems less likely to be problematic in tools designed by statisticians or engineers specifically for technical analyses. We expect that as peer review of assessments increases, the use of spreadsheets for formal fishery analyses will be de-emphasized in favor of tools whose code can be more readily examined and verified. Examples include the S programming language (implemented as the open-source language R and the commercial package S-PLUS), traditional programming languages such as Fortran (whose current versions include array operations as part of the language) and commercial and open-source toolkits such as Matlab, Octave, and AD Model Builder.[2] We hope that fishery educators in particular will carefully consider whether spreadsheets alone are the best tools for teaching data analysis and good programming habits to new fisheries professionals.

7. Population dynamics of increasing stocks. For most marine fisheries in the U.S. and elsewhere, historical population patterns have ranged from a more-or-less stable state to a sharp decline. In relatively few cases have we experienced full recovery from depletion to high levels of abundance. In the New Industrial Age, fishery modeling will face new challenges in understanding the recovery dynamics, including predicting recovery rates, of currently overfished stocks. Population trips up may not be the same as the trips down, which may spark new developments in the theory of fishing and corresponding new model configurations.

8. Efficiency in data collection and use. It is easy to compile a long list of data desirable for accurately assessing a stock. Such a list would include time series of age and length frequencies from each fishery, a fishery-independent survey designed to sample abundance and age-composition of the stock precisely, detailed spatial information on movement and distribution at all life stages, information on environmental influences, and understanding of interspecific relationships. However, it is not always obvious which of those data are most important for making accurate projections and giving robust management advice for a given stock. In general, fishery management has focused on single-stock management, and assessment science has focused on single-stock assessment. Because the stock is the target of management in most areas, that focus is unlikely to change soon. However, because of the economics of fisheries and the rarity of some species, collection of sufficient data for status determination of every stock is seemingly impossible. The solution to the problem of collecting information for all stocks may come from changes in sampling surveys and data collection methods, which will be forced to become more efficient, both statistically and economically. Data collection methods with the best cost efficiency will be identified through extensive computer simulations, and we trust that development of new sampling designs will explicitly accommodate needs of assessment models for multiple stocks.

Meta-analyses, already currently in use for some fisheries (Liermann and Hilborn [1997], Myers and Mertz [1998]), will be employed more extensively. The economics of fisheries and increasing depletion of formerly unimportant stocks may force sampling designs to reduce sampling intensity of some more important or abundant stocks in exchange for increased sampling of less valuable or less abundant stocks.

Environmental data are currently employed in some fisheries management plans (e.g., Pacific Sardine FMP), and we envision further use of environmental data, especially given the promising advances in climate data collection and prediction. Fisheries oceanographers may provide accurate recruitment predictions based on egg and larval fish dynamics for some stocks. It may be determined that effective management of some recruitment-driven fisheries can be accomplished with simple recruitment-prediction models.

9. Concluding remarks. There will be incremental advances in fisheries population modeling in the next decades, but in large part we agree with Quinn's [2003] assertions that the "Golden Age" of fisheries model development has passed. Much research in the immediate future is likely to focus on determination of the necessary data for stock assessment and the efficient collection of those data for stocks of concern, with the economic and social values of the resource guiding the process. In that respect, management techniques may need to evolve to become less demanding of data.

In this new age, the resources devoted to collecting data on fish populations may stop increasing or even decline, but pressure to assess each stock affected by fishing (whether as a target or through incidental mortality) will increase. As a result, sponsored work on fish natural history may be more tightly linked to assessment needs. An extreme vision has data collection, model evaluation and management advice interlinked, in a semi-automated framework providing immediate updates of catch quotas and population status for managed stocks. An alternative to that high-tech (and high-information) vision would be operating some fisheries as "low-information" systems (MacCall [1990]) in which information gathering must be, above all, cost effective, and in which the fishery is severely limited so that management techniques and assessment models are robust to uncertainty. Assignment of property rights in fisheries could be one way of moving to less information-hungry management schemes (Bromley [1992], Rosenberg [2002]).

The future of fishery modeling will be dictated by the future of fishery management. Unfortunately, present fishery management in many places seems to have "locked themselves into policies and operating procedures that require intensive research and monitoring efforts" (MacCall [1990]). That situation resulted in the Golden Age of fisheries modeling, i.e., the development and refinement of increasingly complex population models based on simple and coherent theory. The future Industrial Age of fisheries modeling will, we hope, provide some feedback, encouraging fishery management to re-think its strategies, at least for some fisheries.

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ENDNOTES

1. Views expressed are those of the authors and may not correspond to those of NOAA or any other government agency.

2. Reference to commercial and noncommercial products does not constitute or imply endorsement by NMFS, NOAA, any government agency, or the authors.

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