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THE EVOLUTION OF QUANTITATIVE MARINE FISHERIES MANAGEMENT 1985–2010

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ABSTRACT. This paper reviews the changes in quantitative marine fisheries management between 1985 and 2010. The two primary areas where quantitative methods have been employed are in the assessment of stock size and exploitation rates, and in the design and evaluation of harvest strategies. In 1985, some areas had well established assessment programs in place, and the assessment methods have been relatively stable over the 25 years in question. In other places, the evolution of methods has been much more dramatic, and where there were either no assessments performed or early virtual population analysis (VPA) was done using mainly catch-at-age data, complex statistical models using maximum likelihood or Bayesian statistics are now common. Harvest strategies have generally evolved even more. In 1985, most harvest strategies were based on fixed exploitation rates from yield-per-recruit analyses. By 2010, most agencies had adopted harvest strategies that specifically reduced exploitation rates as abundance dropped below the biomass that will produce maximum sustainable yield. Simulation testing of these harvest strategies has become an integral part of their design, often using the uncertainty from the assessments to bound the robustness trials for the harvest strategy. Two major areas of new quantitative methods are (i) spatially explicit models that can be used for marine spatial planning, and (ii) in ecosystem models to evaluate ecosystem wide impacts of fishing.

KEY WORDS: Quantitative methods, stock assessment, harvest strategies, fisheries management.

1. Introduction. The period from 1985 to 2010 saw the transformation of world fisheries management. In 1985, most countries had recently declared 200 mile exclusive economic zones, and many were

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just beginning to develop the scientific and institutional infrastructure to manage fisheries. Most fisheries were open-access and few had hard limitations on total catch. World fishing power had been growing as had the total world catch. We know now that the seeds of overexploitation had been set, and the management systems were not prepared to prevent it.

In 1985, the scientific institutions for data collection and management were in place in many parts of the world. In Europe, ICES had been founded in 1902, concerns about the impact of fishing pressure was over 100 years old, and there was a long history of scientific research and surveys of fish stock abundance (Smith [1994]). In North America, many fisheries were heavily developed, with hundreds of years of industrial fishing in the east coast, and systematic surveys had been established in the 1960s that continue today. On the west coast, the International Pacific Halibut Commission (IPHC) had been established in 1923, and had a sophisticated stock assessment system in place and was considered a model for international cooperation and scientific management. The sardine fishery had boomed and collapsed in California, as had the major crab fisheries of Alaska. The fisheries for groundfish, off the west coast and in Alaska were still developing, and a time series from surveys were becoming available.

Between 1985 and 2010, a great number of changes have taken place. Many stocks have been overfished or depleted including the well-known declines of most North Atlantic cod stocks, bluefin tuna, and a range of demersal species, particularly, in the North Atlantic. This period has also seen the rebuilding and recovery of numerous formerly depleted stocks including the Peruvian anchoveta, North Sea herring, Arcto-Scandinavian herring, California sardine, New England, and North Sea haddock. Many countries have built large fisheries management establishments with scientists, research vessels, and budgets. Stock assessment methods have evolved from methods that largely used one or two types of data to flexible methods that can use almost any kind of observation. On the policy side, management complexity has increased with this increased information and the number of objectives has grown. Nongovernmental organizations have become involved in fisheries management, and advocacy for marine protected areas, protection of marine mammals, and sport fishing has become part of the policy debate in many regions.

By 2010, many countries and international organizations have developed a fisheries management structure and process that has many common elements including (i) an annual data collection program that estimates catch, trends in abundance from research surveys, size and/or age composition of the population, and the catch; (ii) an assessment process that uses population dynamics models to estimate the trend and current population size, productivity, and fishing mortality rate; (iii) a harvest control rule that uses the output of the assessment to determine the allowable harvest; and (4) a monitoring and surveillance system (often using observers) to assure that regulations are followed.

Quinn [2003] described the development of methods during this period, which he called "The Golden Age." At present, in industrial fisheries, stock assessments are largely based on two approaches. Statistical catch-at-age or -length (SCA or SCL), or variations on tuned-virtual population analysis (VPA). Quite frequently, tuned VPA models are used in fisheries with high exploitation rates and consistent catch-at-age data, and a longer history of analysis (e.g., from the 1970s). This approach has traditionally been used for most North Atlantic stocks. SCA and SCL models are used in fisheries where age data are generally less available (especially in consecutive years). This would include most temperate fish in the western US and Canada, Australia, and New Zealand.

In the mid 1980s, few methods were based on statistical formulations using likelihood and many parameters, rather they typically used sums of squares and estimated relatively few parameters. The VPA models used at that time often had only one free parameter (the fishing mortality rate in the last year often called "terminal F") that was estimated by manual tuning. The stock recruitment and biomass dynamics models that were used had only a handful of free parameters, and the most common computer algorithms to minimize sum of squares was either the Simplex method, or quasi-Newton algorithms.

In the intervening 25 years, many models began to use maximum likelihood or Bayesian approaches, and the number of parameters that could be estimated exploded. It is common for a modern SCA or SCL model to estimate at a minimum, a recruitment for every year and every initial age class, and two to four selectivity parameters for every fishing fleet, requiring 30–70 basic parameters. In addition, many models allow for a wide range of annual deviations in selectivity, often through mixed effect or state–space models, effectively estimating hundreds of parameters. These developments were due to the fact that computer software had become much more sophisticated and almost all SCA models use some form of automatic differentiation to find the best estimates such as the package AD-Model Builder (ADMB, Available from http://www.nceas.ucsb.edu/news/admodel) (Fournier [2011]).

Within SCA models, Bayesian methods are now often used to describe uncertainty, and to include prior distributions for parameters derived from meta-analysis. A major impetus for using SCA models is their ability to incorporate almost any form of data, be it surveys, length- or age frequency, tagging, or genetics (Methot [2000]).

The data used for fisheries stock assessment remains, primarily, estimates of total removals, fishery independent surveys, age and length structure of the catch and/or population, and fishery dependent indices of abundance such as catch per unit effort (CPUE). Fishery independent surveys have become more common, and methods of acoustic surveying have advanced considerably. The frequency of observer coverage has increased so that better estimates of discards and age and length frequency sampling of catch has improved. Considerable work has taken place in standardizing CPUE (Maunder [2001]). Major changes in tagging technology have taken place, most notably the use of internal coded-wire-tags (CWT) and passively interrogated tags (PIT) that allow determination of tag frequency in catch without relying on fishermen's returns of external tags. The use of archival tags that provide various forms of geo-location of individual fish has been important in understanding biology and stock structure, but few archival tagging studies are extensive enough to provide sufficient data to include in stock assessments, and the use of archival tagging data in assessments is largely confined to large tunas and billfish. Acoustic tagging and tracking has developed in the last 25 years, but to my knowledge has been used almost exclusively to refine biological understanding and has not yet been used in assessments.

In 1985, the most common harvest strategies involved a fixed exploitation rate—often derived from the calculation of yield-per-recruit. Most current harvest strategies aim for a fixed target exploitation rate when stock sizes are above biomass at maximum sustainable yield (BMSY) or a proxy, but the target harvest rate is more commonly derived from spawning-biomass-per-recruit rather than yield-per-recruit and the targets are now generally lower. Most current harvest strategies now include provisions for reducing target harvest rates when stocks decline below BMSY, and very commonly include a lower biomass limit, below which either all directed fishing stops, or specific rebuilding plans must be developed.

In 1985, most fisheries relied on technical measures such as size limits or mesh size, vessel size, season lengths, and closed areas to restrict fishing mortality. Actual hard total allowable catches (TAC) limitations were relatively uncommon, and the majority of fisheries were open-access—that is anyone who wanted to go fishing could obtain a license for a nominal sum. The intervening 25 years have seen dramatic changes with most fisheries now using hard TAC limits on total catch, and open-access almost completely disappearing. Also, now quite common are various forms of catch shares, in which individuals or vessels are assigned a specific share of the allowable catch through individual vessel quota (IVQ) or individual transferable quota (ITQ's), or group allocated fixed shares of the TAC.

In the subsequent portions of this paper, I will describe the 25 years of changes in some detail for a range of specific fisheries, then summarize what I see as the important trends and the prospects for the future.

Quantitative science has played a very important part in the evolution of fisheries management, scientists trained in a range of fields, from physics to statistics and biology have been the architects of the stock assessment methods, and commonly, the harvest strategies and data collection schemes. This paper will trace the evolution of these elements of fisheries management and the role of quantitative science over this period. In the next section, I describe the assessment methods, harvest strategies, and regulatory mechanisms for a range of fisheries. Tables 1–3 summarize this information for each fishery. These fisheries represent a range of national and international fisheries, and include some stocks where the assessment methods were well developed by 1985 and others where the methods have changed dramatically.

2. Case studies

2.1. US salmon and pollock and Pacific Ocean perch. The Bristol Bay sockeye fishery is the most valuable salmon fishery in North America and exemplifies stable and sustainable management.

TABLE 1. Assessment methods used for different fisheries.

Fishery	1985	2010
Bristol bay sockeye	Ricker stock recruitment model	Ricker stock recruitment model
Bering sea pollock	Tuned VPA	Statistical catch-at-age
West coast POP	Statistical catch-at-age	Statistical catch-at-age
Pacific halibut	Statistical catch-at-age	Statistical catch-at-age
Northern cod	Tuned VPA but poor model used	No recent assessments due to closure
NZ hoki	None	Statistical catch-at-age
NZ rock lobster	Biomass dynamics, yield per recruit	Statistical catch-at-length
North sea groundfish	Tuned VPA	Tuned VPA
Australian SE trawl	Schaefer production model (3 stocks)	Statistical catch-at-age (12 stocks)
Australian shark	None	Statistical catch-at-age
Australian blue grenadier	Area swept biomass estimate	Integrated analysis
Southern bluefin tuna	VPA	Statistical catch-at-age
Atlantic bluefin	Tuned VPA	Adapt VPA
Chilean jack mackerel	None	Statistical catch-at-age
Antarctic krill fishery	None	Total biomass with stochastic mortality and recruitment
Subantarctic island finfish fisheries	VPA	Statistical catch-at-age

This is a fishery where the basic approaches have changed little (Hilborn et al. [2003], Hilborn [2006]). The salmon live in the oceans for several years and then return to their natal streams to spawn. The fish are caught just before they enter freshwater. The number of fish escaping past the fishery and migrating up rivers to spawn has been counted consistently since the 1950s and along with catch data, allows the management agency to determine the annual spawning stock,

TABLE 2. Harvest strategies for each fishery.

Fishery	1985	2010
Bristol bay sockeye	Fixed escapement goal	Fixed escapement goal
Bering sea pollock	$F_{0.1}$ harvest rate + 2 million t total harvest cap	Risk-averse harvest rate and 2 million t total harvest cap
West coast POP	F < FMSY (rebuild depleted stock, minimize direct targeting)	Rebuild within mandated time frame
Pacific halibut	Fixed harvest rate	Fixed harvest rate
Northern cod	$F_{0.1}$ (F always higher in fact)	Closure until SSB rebuilds to minimum
NZ hoki	None	Risk-based harvest rate versus biomass
NZ rock lobster	Size limit	Target CPUE
North sea groundfish	Status quo F	Detailed recovery plans specifies targets
Australian SE trawl	Size limits for some stocks	Risk averse harvest strategy— MEY target, zero harvest rate below a limit
Australian shark	None	Risk averse harvest strategy — MEY target, zero harvest rate below a limit
Australian blue grenadier	None	Risk averse harvest strategy – MEY target, zero harvest rate below a limit

(Continued)

TABLE 2. *(Continued)*

Fishery	1985	2010
Southern bluefin tuna	None	*Ad hoc* changes in TAC
Atlantic bluefin	None	FMSY
Chilean jack mackerel	Size limits	Size limits, *ad hoc* TAC adjustments
Antarctic krill fishery	None	Risk-based and ecosystem-based, with objective of achieving B/B0 = 0.75 after 20 years harvesting; area subdivision to protect breeding predators
Subantarctic island finfish fisheries	None	Risk-based, with objective of achieving B/B0 = 0.50 after 35 years harvesting

and the subsequent production. These data are used to fit spawner recruit curves so the optimal spawning stock sizes can be estimated. Unlike most marine fisheries, the management system aims for a constant number of fish spawning, rather than target harvest rates. The pattern of areas open to fishing is adjusted daily within the fishing season to try to allow the actual number of fish escaping the fishery to be near the level that will produce long-term maximum sustainable yield. The fishery has had a limited number of licenses since the mid 1970s, but for the boats permitted to fish, there is a competitive fishery.

This management system has changed reasonably little in the last 25 years. Considerably, more work has gone into treatment of uncertainty in the fitting of stock recruitment curves, and the actual

TABLE 3. Regulatory mechanisms for each fishery.

Fishery	1985	2010
Bristol bay sockeye	Time and space closures	Time and space closures
Bering sea pollock	Area closures, prohibited species limits, OY cap	TAC by sector
West coast POP	TAC and bycatch allowance per trip	TAC
Pacific halibut	TAC by country: season length	TAC by country: ITQs
Northern cod	TAC by Canada sector and by NAFO	Closure
NZ hoki	None	TAC and ITQ
NZ rock lobster	Input controls size limits, fleet limits	TAC and ITQ
North sea groundfish	TAC by country, technical measures	TAC by country, technical measures, some effort restrictions
Australian SE trawl	Input controls, some size limits	TAC with ITQ, supplemented with area and gear controls
Australian shark	Input controls, some size limits	TAC with ITQ, supplemented with area and gear controls
Australian blue grenadier	Input controls	TAC with ITQ, supplemented with area and gear controls
Southern bluefin tuna	None	TAC by country
Atlantic bluefin	None	TAC by country
Chilean jack mackerel	Size limits	Size limits, TACs by region and company

(Continued)

TABLE 3. *(Continued)*

Fishery	1985	2010
Antarctic krill fishery	No management	Global TAC, divided by area, and season, with notification but still Olympic fishery
Subantarctic island finfish fisheries	No management	Nationally imposed individual quotas, under over-arching CCAMLR defined TAC

spawning stock targets have been adjusted as new data became available, but the overall nature of the fishery management system was considered successful in 1985 and remains largely the same today.

The Bering Sea pollock is the largest fishery by volume in the United States. Prior to the 1990s it was largely a foreign fishery, but through joint-venture operations of the 1980s foreign fishing was phased out. By 1985, the United States had established surveys of pollock abundance and estimated age composition from the surveys and from commercial catch. The assessment method was a tuned VPA, and the TAC was set based on a $F_{0.1}$ exploitation rate, but the total catch was constrained by an ecosystem wide cap of 2 million tons total harvest. This had the result of keeping the catch often well below the potential catches under the harvest strategy. In 1985, there was an Olympic race-to-fish within constraints imposed by seasons and closed areas. By 1997, the assessment method had shifted to a SCA model (Ianelli et al. [2010]) and a formal harvest strategy was in place that defined the target exploitation rate as a risk-averse estimate of fishing mortality rate at maximum sustainable yield (FMSY) which was adjusted downwards dramatically as stock size drops below BMSY. Above BMSY, the 2 million ton total catch cap effectively constrains the pollock catch from exceeding about 1.5 million tons. This means that at high stock sizes the harvest rate declines. The TAC is allocated by season (no more than 40% can be taken during the spawning period) and between shore-based and at-sea processing sectors.

Pacific Ocean perch is caught mainly in the Gulf of Alaska and Aleutian Islands but extends through Canada and the US west coast down to central California and was the subject of a targeted foreign trawl fishery prior to the United States declaring the 200 mile exclusive economic zone (EEZ). Presently, this species is harvested by the domestic trawl fisheries of the United States and Canada. Because of the large removals due to intense foreign fishing prior to 1985, it was among the first domestic fisheries to be assessed. In 1985, the stocks in the US waters were assessed using VPA and the harvest strategy was to keep fishing pressure below FMSY in order to allow the stock to rebuild. By 1992, a formal SCA model had been developed and grew in complexity and sophistication. In both the Alaskan waters and off the US west coast the stocks have undergone formal rebuilding plans (with recoveries completed in the Gulf of Alaska; the US west coast stock is still estimated to be below the target level).

2.2. Pacific halibut. Pacific halibut has a long history of management by the IPHC (established in 1923) and was one of the first organizations to actually regulate catches through TACs. The IPHC established data collection programs of longline surveys, analysis of age and length distributions, mark-recapture, and tracking fishery CPUE. The SCA program CAGEAN (Deriso et al. [1985]) was one of the first implementations of modern SCA models (albeit with a simple sums-of-squares objective function), and was used for the halibut assessment in 1985. Their management system has evolved but remains largely the same. The SCA models presently use modern software (ADMB), the spatial structure of the assessment has changed, and tagging and survey methods have been updated. The harvest strategy remains essentially a fixed exploitation rate. The biggest change in halibut management has been in the harvest regulations. In 1985, in both the United States and Canada, there was a global TAC with a race-for-fish regulated by season lengths which led in the late 1980s to 1 and 2 day fishing seasons in Alaska. In both, Canada and Alaska, there is now an ITQ system that assigns each vessel a specific share of the catch and the fishing season now lasts 6 months.

2.3. Northern cod in Canada. After Canada declared a 200 mile EEZ in 1977, the northern cod fishery was the largest fishery in Canada and was an example of state-of-the-art fisheries management. Fishery independent surveys were conducted and tuned VPA was used. The harvest strategy was a fixed harvest rate aiming at 20% annual exploitation. The Northern Cod fishery in eastern Canada is well known because of its importance to the economy of Newfoundland and its total collapse and fishery moratorium instituted in 1992. The stock remained at very low abundance with almost no sign of recovery despite the fishing moratorium until the mid 2000s. Since that time some increase is apparent but the stock remains at a very low level of abundance (Schrank [2005], Rice [2006]).

In retrospect the assessments were overestimating the stock size significantly so that the actual exploitation rate was much higher than the target. This was in part due to unreported discarding and possibly a change in environmental conditions that reduced stock productivity. The cause for the failure of the stock to rebuild since the 1992 moratorium is unknown. At present, management and assessments focus on tracking the trend in abundance through surveys even though directed fishing remains limited.

2.4. New Zealand hoki and rock lobster. New Zealand hoki is the largest fishery by volume in New Zealand and produces a white fish product that competes with pollock, cod, and hake. In 1985, New Zealand had a fishery management system that was just developing so early data were limited to catch and effort and the fishery was essentially unregulated. In 1987, New Zealand instituted a Quota Management System (QMS) for most of their fisheries that required setting an annual TAC for hoki and an ITQ system to divide the commercial catch among competing vessels. They also instituted trawl and acoustic surveys along with fishery length and age sampling. The assessment methods evolved rapidly through the 1990s and by 2000 they developed and used a standard package known as CASAL (Bull et al. [2005]) that is a SCA model that can be fit to age distribution or length distribution. Uncertainty in the assessment is described using Bayesian analysis. New Zealand has recently introduced a harvest strategy that specifies the TAC as a function of the stock abundance.

The rock lobster fishery in New Zealand is one of New Zealand's most valuable fish stocks and developed rapidly following World War II as export markets became available. The earliest stock assessments, developed in the 1980s were biomass dynamics models fit to a history of catch and CPUE (Saila et al. [1979], Annala and Breen [1988], Breen [1988]). In addition, yield-per-recruit analysis was also conducted using estimated growth, maturity, and vulnerability at age. Regulation was primarily a size limit combined with a limited entry. In the early 1990s the rock lobster fishery entered the New Zealand QMS and annual TACs are set for each of the statistical regions. The stock assessment has now evolved to using a SCL model, using data from an industry organized length frequency and CPUE sampling program. The actual TACs are set for the major fisheries by a pre-defined "decision rule" (Starr et al. [1997]) that adjusts the TAC in relation to the CPUE.

The data used as inputs to the assessment and decision making are the catch, length frequency, and CPUE. Unlike most other fisheries described here where the outputs of the assessment feed directly into the decision process, in this fishery the assessment is only used to evaluate the robustness of the decision rule to uncertainty in the stock biology and observation of the stock status. Uncertainty in the assessment model is described using Bayesian analysis.

2.5. North sea groundfish. The assessment methods for North Sea groundfish have remained quite stable over the last 25 years. The data used for assessment have consistently been research surveys, estimates of total catch, and the age structure of the catch and surveys. Tuned VPA was used in 1985 and the same basic approach is used at present. The management system has changed considerably more. In 1985, the harvest strategy was a constant exploitation rate estimated to hold the stocks at their current level—often called a "status quo F." For a variety of reasons, including discarding, unreported catch, and TACs being set above the science advice, many of these stocks declined after 1985, and now are subject to stock specific rebuilding plans. For instance, since 2004 the science advice for North Sea cod has been zero catch, but the bycatch of cod in other fisheries remains a major problem. The major regulatory structures have also remained consistent. Individual countries are allocated TACs, and a range of technical measures are applied, which differ within countries.

2.6. Australian fisheries. The Australian Southeast trawl fishery (Smith and Smith [2001]) is a typical mixed-species trawl fishery capturing a range of species. In 1985, the only data available were catch and estimates of CPUE, and three of the most important species were assessed using biomass dynamics model fit to the CPUE trend. There was no formal harvest strategy except for limitations on vessel numbers and some technical measures such as size limits. At present, there are new research survey and age-composition data available, and the assessment uses a SCA model for 12 individual stocks. There is a formal harvest strategy in place with the target exploitation rate constant above a specified level (Smith et al. [2008]), and declining to no harvest at a lower limit reference point. An annual TAC is set and catches are assigned to individual vessels through an ITQ program.

Two species of shark, school shark and gummy shark, have been important commercial fisheries in southern Australia. In 1985, there were research survey, CPUE, length frequency, and tagging data available, but no assessments were performed, no harvest strategy was in place, and the only regulations were input controls on vessel numbers and gear. At present the same data are available, but there is now a SCA model used. The same type of harvest strategy used in the Australian Southeast trawl fishery is applied for sharks, and there is also a TAC set and individual allocations via an ITQ program.

In Australian waters, blue grenadier *Macruronus novaezelandiae* (called hoki in New Zealand) are found from New South Wales around southern Australia to Western Australia, including the coast of Tasmania. Catches of blue grenadier were very small until the late 1970s and until 1985 the fishery (then called the South East Trawl) was effectively open-access. Limited entry was brought into the fishery in 1985. TACs for blue grenadier were introduced in 1992. In 2010, the primary management tool for blue grenadier is as part of a QMS with TACs allocated as individual transferable quotas to 34 species or stocks in the SESSF. Other measures in the SESSF include input (vessel numbers) and gear (e.g., mesh size) controls and, in recent times, extensive spatial management, including spatial closures. A harvest strategy policy for all Commonwealth fisheries was introduced in 2007 that sets limit and target biomass reference points with explicit control rules (Smith et al. [2008]).

2.7. Bluefin tuna. The southern bluefin tuna (SBT) fishery was originally developed after World War II by Japanese longliners fishing primarily in the Indian Ocean. Australian purse-seiners discovered they could capture large quantities of juvenile SBT off of West Australia, and in the 1960s the Australian fishery developed and eventually moved east in Australia where larger 2–4–year-old fish were available for seining in the Great Australian Bight. Now almost all the Australian catch is captured live, put in feeding pens, and raised for several months to increase weight, before being shipped to Japan for the sashimi market.

In 1985, early assessments were using tuned VPA, based on length frequency data from the catches. No harvest strategy was in place, and Australia, Japan, and New Zealand were in negotiations to determine stock status and to determine the need to reduce fishing pressure. By the 1990s the three countries had reached agreement on the need to reduce catches and individual country allocations had been agreed and the Commission for the Conservation of Southern Bluefin Tuna had been formed. By 2010, Korea, Taiwan, and Indonesia had also joined the commission. The stock assessment method had evolved to a complex fleet and season specific SCA model fit to both age and length data. The global TAC was allocated by country, and within Australia and New Zealand catches were allocated through an ITQ system whereas in Japan catches were allocated to individual companies. No formal harvest strategy had been adopted although the scientific committee of the Commission had been working for years on developing a formal management procedure.

In recent years Atlantic bluefin tuna have become the poster child of fisheries in trouble. In 2010, it was proposed for listing on Appendix I of CITES based on arguments that it was threatened with extinction. In 1985, the only data available were CPUE and length distributions. The stock was assessed using tuned VPA, and the management agency, the International Commission for the Conservation of Atlantic Tunas set annual catch quotas for each country. No formal harvest strategy was in place. By 2010, data on age structure and tagging were available and the assessment had changed to the ADAPT version of VPA. A harvest strategy of FMSY was adopted, and national TACs were established.

2.8. Chilean jack mackerel. The fishery for jack mackerel in Chile is one of the largest fisheries in the world with catches over 4 million tons per year in the mid 1990s. In 1985, the major regulation was a mesh size of 2 inches, there was no formal stock assessment, and no harvest strategy was in place. By 2010, the assessment was done with SCA models, the TAC was set in relation to abundance but without any formal harvest strategy, and TACs were allocated by company to form a system much like an ITQ.

2.9. Antarctic fisheries. Some of the newest fisheries in the world are those of Antarctic waters, both the international waters managed by the Convention for the Conservation of Antarctic Living Marine Resources (CCALMR) and in the territorial waters of nations in sub-Antarctic Islands. Antarctic krill remain one of the largest biomasses of exploitable resources in the world. No assessments were performed in 1985 but there were surveys, CPUE and size distribution data available. Catches of krill have generally remained small, well less than 100,000 tons despite the biomass being well in excess of any fish population in the world. By 2010, a formal harvest strategy of maintaining the abundance at least as high as 75% of the estimated unfished level after 20 years of harvesting had been adopted. In addition specific areas of special importance to predators were provided additional protection. A global TAC is set each year, by area, but within those constraints there is an Olympic style competitive system to catch the TAC. The assessment model used is a specially developed biomass dynamic model that explicitly includes stochasticity in natural mortality and recruitment.

Sub-Antarctic Island finfish have been of particular international interest, especially the Patagonian toothfish of South Georgia Island which were the subject of much international controversy when they were certified as well managed by the Marine Stewardship Council. In 1985, data from surveys, CPUE, and age sampling were available and a VPA was performed. There was no harvest strategy and no real management. In 2010, the assessment method is a SCA model, and a harvest strategy is employed designed to reduce the biomass to 50% of the unfished level over 35 years of fishery development. CCALMR imposes an overall TAC and within this there are individual quotas (Candy and Constable [2008]).

3. Discussion

3.1. Evolution of assessments. The evolution of methods available for stock assessment is well described in Quinn [2003]. The major development in methods has been the SCA models that have evolved from the 1970s and 1980s models of (Doubleday [1976], Fournier and Archibald [1982], Deriso et al. [1985], Methot [1989]). A simultaneous increase in computing power, application of maximum likelihood and Bayesian methods, better numerical algorithms, and a desire to integrate all available information into the assessments led to this evolution. Theoretically the major advantage of these methods is the ability to estimate the uncertainty in management quantities of interest, especially current stock size, and exploitation rate that would produce maximum sustainable yield. As discussed later, the actual harvest control rules rarely use uncertainty estimates and rely primarily on the most likely estimates of the parameters from the assessments. Instead the harvest control rules are designed to be robust to the uncertainty.

An interesting feature of the development and evolution of methods is the contrast between the North Atlantic fisheries, and particularly Europe, and most of the rest of the developed world. ICES and the North Atlantic in general are the source of most of the original development of fisheries science (Smith [1994]), but in the last 25 years the development of methods, and changes in assessment methods have primarily occurred outside of the N. Atlantic. For instance all of the modern SCA and SCL or other integrated methods have been developed outside the N. Atlantic. Analysis of citations of scientific papers shows an overwhelming dominance of work from Pacific Canada and the United States. While most national and international management agencies have adopted these new methods, ICES and to some extent Atlantic Canada and Eastern US still largely use variations on the VPA methods used in 1985.

I suggest several reasons for the relative stability of N. Atlantic methods. The VPA methods appear to work well when two key conditions are met, consistent high quality catch-at-age data are available, and exploitation rates are in general high. The major industrial fisheries of the N. Atlantic commonly meet these criteria. In contrast much of the rest of the world has data sets that may begin with very low exploitation rates, and have only intermittent or more uncertain catch-at-age data. Overall exploitation rates in much of the rest of the world, particularly the Pacific coasts of the United States and Canada, tend to be much lower. Furthermore, within the ICES context there are major advantages to all assessments using a consistent analytic framework since so many countries, languages, and individuals are involved. Whereas on the Pacific coast government laboratories have tended to evolve using a range of methods able to use the available data throughout the last 25 years, ICES had settled on an approach by 1985 that meets their scientific needs.

3.2. Evolution of harvest control rules. The second area of quantitative fisheries management that has evolved considerably has been in harvest control rules. In 1985, most fisheries had either no formal rules, or primarily adopted some variation on a fixed exploitation rate strategy. The concern about overfishing, and increasing emphasis on the environmental consequences of fishing have led to adoption of formal harvest strategies in the United States, Australia, Iceland, and New Zealand and often to explicit consideration of risk. These strategies differ from the earlier fixed harvest rate strategies in several aspects. First they decrease the harvest rate, usually to zero, as the stock abundance declines below some level, usually somewhere around the biomass that would produce maximum sustainable yield. Second they generally have a maximum harvest rate that is distinctly lower and more precautionary, often set based on spawning biomass per recruit calculations (Clark [1991, 1993]). Australia, for instance, formally sets its target abundance at a proxy for economic optimality that is 120% of the biomass that would produce maximum sustainable yield (Department of Agriculture Fisheries and Forestry [2007]). In the United States, the harvest rate that would produce maximum sustainable yield is now considered a maximum limit rather than the target.

Management strategy evaluation (MSE) is the simulation of the consequences of a combination of data collection, assessment method and harvest control rule (Punt et al. [2001], Butterworth [2007], Dichmont et al. [2008], A'Mar et al. [2009]). In its most sophisticated form MSE involves specifying a range of hypotheses about the biology of the fish and the nature of the data collection process, and evaluating assessment approaches and harvest control rules. Since they may involve simulating the complex catch-at-age or catch-at-length assessment models many thousand or even million times this kind of analysis can stretch existing computing power. It is perhaps the most computationally intense aspect of modern quantitative fisheries management, and I believe now widely accepted as an important part in understanding the performance of an assessment method and harvest control rule.

4. Conclusions. The evolution of quantitative fisheries management cannot be isolated from other developments in fisheries management. For instance, assessment methods are often driven by legal requirements of the management system. When New Zealand went to an ITQ system in the 1980s the research scientists were forced to provide scientific recommendations about allowable catches—thus generating the assessment system now in place within New Zealand. In the United States, the mandate to set annual catch limits for all fish stocks is forcing a new round of methods development for situations with a lack of traditional assessment data. Assessments for "low information" stocks has become a high priority. The push for establishment of Marine Protected Areas by non-governmental organizations and legal requirements, is stimulating the development of quantitative methods for analysis of spatially explicit population and ecosystem models (Pauly et al. [2000], Hilborn et al. [2006], Walters et al. [2007])

The general movement toward ecosystem-based fisheries is prompting considerable discussion about the role of ecosystem models in fisheries management. The two most common models now in place are Ecopath-Ecosim (Pauly et al. [2000], Christensen and Walters [2004]) and ATLANTIS (Smith et al. [2007]) which have the ability, in principle, to evaluate ecosystem wide impacts of different fisheries regulations. At present these methods are not used as replacements for the single species assessment models discussed earlier, but are now commonly used in general ecosystem evaluations of the impacts of fishing.

An ongoing issue within the fisheries management community is the role of model complexity. If we contrast the VPA methods used in ICES with the complex SCL models we see a trade-off between the ability of many individuals to understand and use the assessment method, and the sophistication of the assessment method to fully use the available data, express uncertainty in a statistical way, and capture complex assumptions such as temporal changes in selectivity of fishing gears. I suspect this dichotomy will continue and different agencies will continue to make quite different choices.

My personal preference is to move away from the current approach of taking model outputs and putting these into a harvest control rule to produce the actual regulations that are implemented. The modeling approaches are generally quite opaque, and certainly none of the policy makers or stakeholders can possibly understand the complex statistical models now commonly used. While VPA appears more straightforward, we are often confronted with multiple scenarios under different assumptions, which produce different answers.

My suggestion is that we move toward rules similar to that used in the New Zealand rock lobster fishery—that is the input to the harvest control rule should be data, such as surveys, or CPUE. These values can be averaged or smoothed, but the key is that they are clearly understood. Complex assessment methods are still needed and can be used to evaluate the management strategy, but what is implemented for the regulation setting should be transparent and data driven. An approach with a similar data-drive decision making is known as stoplights (Caddy [1999]) in which several sources of information are used in combination to determine changes in regulations.

The frontier for quantitative methods in fisheries management now seems to be in the ecosystem and spatial components of fisheries management. Many of the hard problems for fisheries managers concern mixed-species fisheries. Whether it is in the North Sea, New England, the west coast of the United States, or Australia, many fisheries catch several species at the same time. At present the quantitative methods used to analyze the interactions between these fisheries and regulations are of *ad hoc* post assessment analysis that could be formalized in multispecies and multifleet models. While such models do exist (Pauly et al. [2000], Smith et al. [2007]) As they said in Star-Trek—space is the final frontier—and this is probably true of quantitative analysis in fisheries management.

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