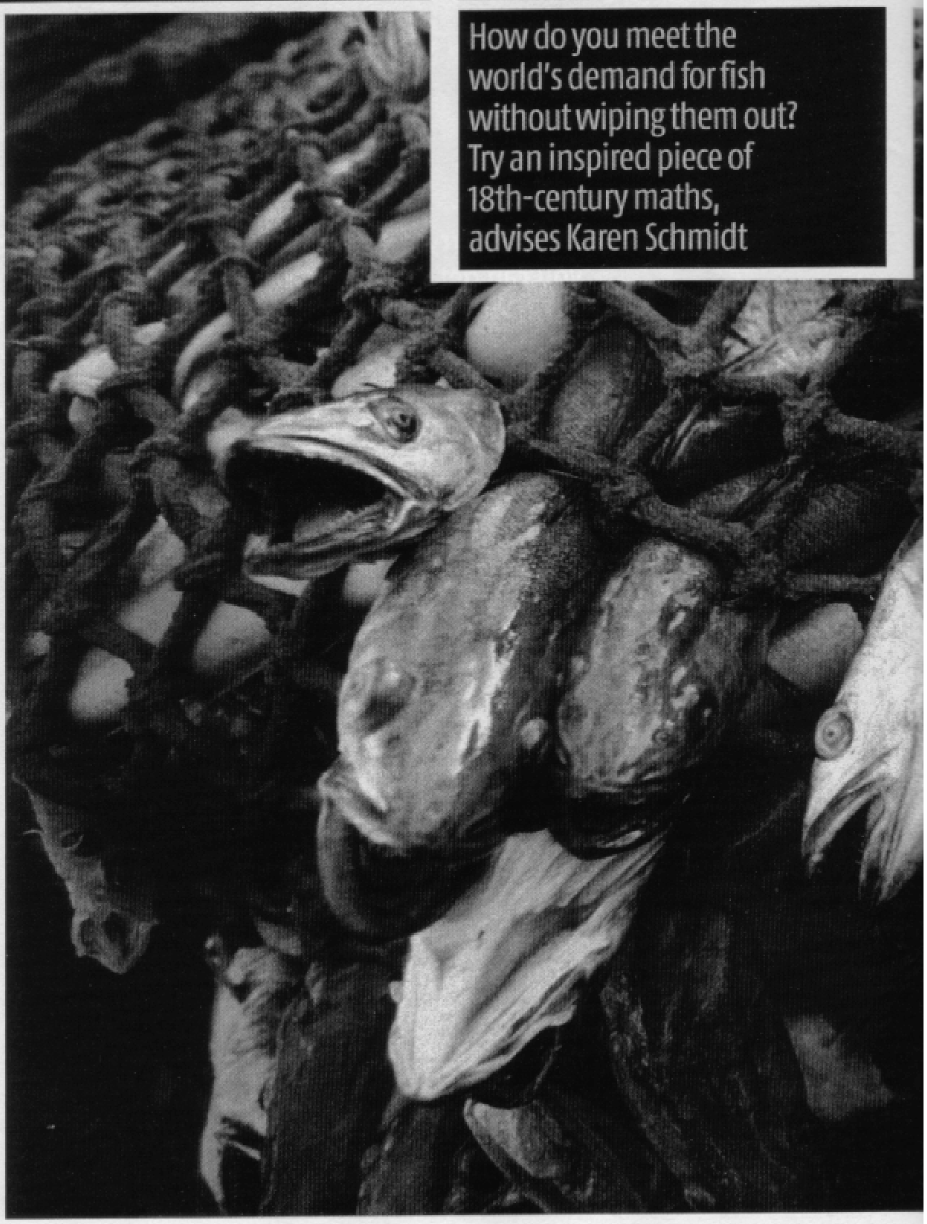
The big catch

How do you meet the world's demand for fish without wiping them out? Try an inspired piece of 18th-century maths, advises Karen Schmidt



GROWING up in Santa Cruz, California, in the 1980s, Teresa Ish would often eat rockfish brought home by her grandfather from boat trips. Her father, too, liked to catch the vibrantly coloured fish, commonly known as Pacific red snapper but actually any one of 50 or so near-shore species.

But by the 1990s, Ish's father had to sail further and further out to sea to find rockfish, until he finally gave up. "He didn't feel he could fish for rockfish any more without harming the dwindling populations," explains Ish, now a graduate student in marine science at the University of California, Santa Cruz. Last September, the Pacific Fishery Management Council finally took emergency action to protect rockfish, banning trawl fishing along almost the entire continental shelf from Mexico to Canada. Scientists are predicting some rockfish populations will take up to 200 years to recover.

What went wrong? You might suspect that fisheries managers had ignored scientific advice. It wouldn't have been the first time: take the depleted cod stocks in the North Sea, for example (*New Scientist*, 27 January 2001, p 16). But in California the scientists got a fair hearing – only their stock assessments were way off. The safe harvest rates they worked out from computer models of rockfish populations were not safe at all. Rockfish numbers sank steadily, defying the models and leaving the scientists baffled.

The crash in rockfish numbers underscores the massive uncertainties in estimating fish stocks and the consequences of getting it wrong. Dissatisfaction with the models has been growing for years and now an increasing number of scientists are saying it's time for a radical overhaul. "No matter how much science we do, there will always be a fairly high level of uncertainty," says Marc Mangel, head of the Center for Stock Assessment Research at the University of California, Santa Cruz. "We need new stock assessment methods that embrace the uncertainties."

Fortunately, fisheries scientists are about to deliver more realistic models. With more powerful computers at their disposal, they are now able to use an arcane branch of probability theory called Bayesian statistics. "This is the most rigorous way to take uncertainty into account," says Murdoch McAllister, a fisheries scientist at Imperial College in London.

How best to estimate the size and productivity of fish populations has been vexing scientists ever since the late 1950s, when the first models were developed, based on terrestrial biology. "Fish are just like trees, except they move and they're invisible," is a common joke among fisheries biologists.

That is the crux of the problem. You must estimate the number of fish with little direct observation. "It's hard enough to say how many fish are in the ocean right now, but we also have to say how many will be there if we catch this much," says Stephen Ralston, a fisheries biologist at the National Marine Fisheries Service in Santa Cruz. "There's a lot of uncertainty." Try thinking of a fish stock as a bank account with an unknown balance. The rate at which the interest accrues is also a mystery. Even so you have to make regular withdrawals without going overdrawn. How much can you afford to take out?

It is not all guesswork. Scientists can estimate the size of a fish stock (the bank balance) from catch data supplied by fishermen. They can also estimate the fish stock's reproductive capacity (the interest rate) by looking at the lengths of fish in the catch. From this they infer the age make-up of the population and how many offspring are likely to be produced. By multiplying the balance and interest rate together they can project the future population size, and figure out how many fish the fleet can safely harvest (the withdrawal amount).

Unsurprisingly, there are many pitfalls in this process, which is known as "virtual population analysis". First, catch data may be inaccurate or exaggerated. The assumption that the length of a fish accurately reflects its age and reproductive capacity is questionable. And biologists are ignorant of the life histories of most of the species they manage and simply make inferences from ones they do know. Worst of all, many of the uncertain parameters in the models are given a fixed estimated value when they would be better expressed as a variable. "From this method you get a very precise result, but it's precisely biased and precisely wrong," says McAllister.

Retrospective studies suggest that virtual population analysis may be at least partly to blame for the collapse of some fish stocks, including cod on Newfoundland's Grand Banks. "The methodology has been found to have a worrying pattern of being wildly optimistic," McAllister says. Nevertheless, it is still the main method used by the International Council for the Exploration of the Sea (ICES), the scientific organisation that assesses fish stocks in Europe.

There have been attempts to do away with virtual population analysis. In the 1990s, Pacific Coast scientists abandoned it in favour of "maximum likelihood" models. The main difference here is that some of the uncertain parameters are expressed as values with a probability of being accurate. That gives scientists a better idea of the uncertainty and allows them to construct a fairer picture of the population.

But it wasn't enough to save the rockfish. With only about a decade of catch data to go on and scant information about rockfish biology, the uncertainties were just too great. In setting fishing quotas, fisheries scientists assumed that rockfish reproduce at rates similar to other fish. Only when it was too late did biologists discover that some rockfish species have unusually long lives and reproduce late in life – yelloweye rockfish, for example, can live to be 100 and don't even breed until they are 20. It also seems that during the 1990s an unusually unfavourable climate lowered the survival rate of young rockfish. By 1998, many stocks were depleted.

Ironically, just as rockfish populations were plummeting, a new tool for dealing with the uncertainties in fish stock assessments finally emerged. With more powerful computers at ▶

Cod stocks slumped when scientists' advice was ignored. But is the advice always right?

their disposal, fisheries scientists could start using Bayesian analysis, a statistical approach particularly suited to dealing with uncertainty.

Bayesian analysis is one of two competing methods for calculating probability – the other being the more common "frequentist" approach. Both have their roots in the 17th-century court of King Louis XIV of France, where Pascal and Fermat argued over the best way of calculating the chances of winning at gambling.

Both men realised that in many gambling games, your chance of winning is related to the outcome of a repeatable event – how often you can expect a particular roll of the dice. But how do you judge the odds of something that is not repeatable and may even be a one-off – like a meteor hitting France? Pascal and Fermat recognised that there is a second, more "subjective" way to approach probability – you can calculate the odds by laying out all the historical information about the same or similar events, as well as all the uncertainties. This approach didn't become formalised until the mid-18th century when an English amateur mathematician, Thomas Bayes, came up with a mathematical formula for judging the probability of future events based on the past, and for revising this probability as new information comes in. But it took the advent of modern computers to make Bayesian probability practical.

To understand the difference between Bayesian and frequentist statistics, imagine trying to estimate the amount of money in the wallets of 400 students in an auditorium. A frequentist would randomly ask nine students to give up their money. Let's say that on average these students carried $35 plus or minus $13. From that, the frequentist estimates that there is $14,000 in the room, with 95 per cent confidence that the real value is between $8800 and $19,200. This estimate is so imprecise because of the large variability of cash carried by students and the relatively small sample size. Surveys of fish abundance suffer from the same problem.

In contrast, a Bayesian would start with a prior estimate – say, that each student is most likely to be carrying $25 plus or minus $20, implying that the total cash ranges between $2200 and $17,800. This "prior" might be based on personal experience, or earlier studies of how much money students carry. The Bayesian would also randomly ask nine students to open their wallets and collect exactly the same data as the frequentist. Then, using Bayes's formula, the Bayesian modifies the prior in the light of the sample data, calculating the mean per student at $32 plus or minus $10, and the total amount of money in the room at $13,000 with 95 per cent confidence that the real value is between $11,300 and $14,800. What you end up with is a more precise and useful estimate. It allows you to take uncertainties into account by factoring them into your priors, and it is easy to update your model when you have new information.

And here is another key difference: Bayesians, unlike the frequentists, can use their model to evaluate alternative hypotheses for how much money there is in the room, analogous to calculating the odds that your estimate of fish abundance is way off. And a Bayesian could also predict future scenarios and calculate their probabilities: for example, how students' money will decline in a poor economy, or how various harvest rates will affect future fish abundance.

That's the beauty of the Bayesian approach and the reason many fisheries scientists believe it's time to make the shift. "Fish are not that predictable and if you act as though they are, you're likely to be caught with your pants down," says Ellen Pikitch, a fisheries scientist at the Wildlife Conservation Society in New York City. "Bayesian analysis helps elucidate the uncertainties."

Pikitch herself was involved in one of the first successful uses of Bayesian statistics in a fish stock assessment. In the mid-1990s, scientists were feuding about the abundance of Gulf Coast sharks, a species caught commercially. On one side were the fish-stock modellers who had calculated a likely rate of population growth. On the other were the field biologists who said the modellers' figure was way too high. A team of government scientists worked with Pikitch, her colleague Beth Babcock and McAllister to recalculate the population rate the Bayesian way and forecast the future abundance of the sharks under different harvest rates. Both sides were satisfied with the new model. Indeed, the Bayesian method is still used for Gulf Coast sharks and the stock assessments have continually improved as new data comes in. "This is an iterative process," says Pikitch, whose team has also used Bayesian analysis to assess North Atlantic tuna and swordfish as well as several fisheries in New Zealand.

The new approach is spreading, and last April Europe's ICES gave its first approval of a

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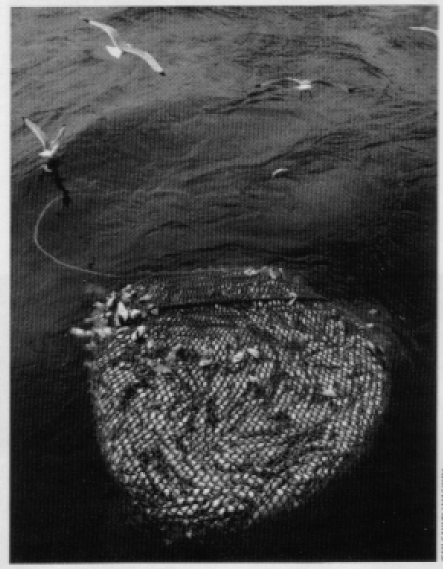
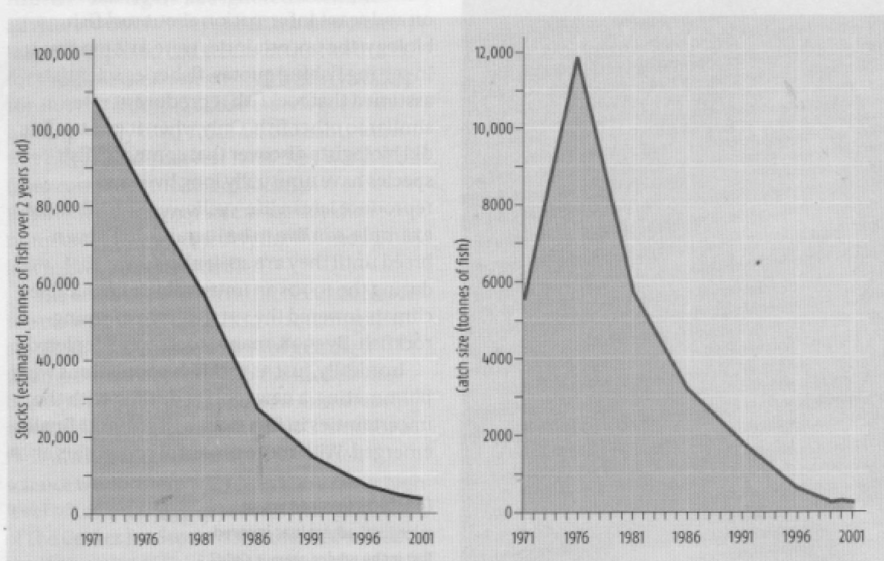


JEAN GAUMY / MAGNUM

OVERFISHING IN THE PACIFIC

Stocks of Bocaccio rockfish off California dwindled steadily throughout the 1970s and 80s despite scientists' claims that catch sizes were sustainable. We now know their models were flawed



New statistical models are already used to assess stocks of North Atlantic swordfish

Bayesian method for stock assessment, in this case to calculate Baltic salmon harvest rates. "This development opens up a whole new gateway for solving some of the methodological problems troubling European fisheries science," says McAllister. His group did the assessment using 15 years of data from Baltic salmon tagged and recaptured, with adjustments to allow for information about the chances of fishermen actually reporting the tags. They concluded that current harvest rates were too high. Consequently, the fisheries managers decided not to increase quotas, as fishermen had requested. With the green light from the ICES, McAllister's group is now looking at applying Bayesian analysis to other fish, such as cod, plaice, whiting and haddock.

Not everyone is convinced that Bayesian analysis is the way to go with fish stocks. Critics are uncomfortable with its subjectivity. First of all, it can lead fisheries biologists to different conclusions from those they would draw from the data alone, says Annette Hoffman, a statistician at Washington state's department of fish and wildlife in Olympia. What's more, two Bayesians can take the same data, choose different starting points, and get two different results – and there's no way to tell which is more accurate. That's because the starting points, or priors, have a big impact on the outcome and often reflect belief or opinion. According to Hoffman, the issue of how Bayesians choose their priors has not been given enough scientific scrutiny. "I consider that what comes out of a Bayesian analysis using a prior function is not probability but updated belief," she says.

Proponents of the Bayesian approach don't deny this, but say it is still better than using frequentist statistics. "Traditional methods have their own hidden assumptions," says Pikitch. "Bayesian is better because the assumptions are transparent and they can be questioned and changed."

A more serious problem is that fisheries managers, the people who actually make the decisions, are not yet geared up for using Bayesian statistics. "The science has gotten ahead of the decision makers," says Ray Hilborn, a fisheries scientist at the University of Washington in Seattle. It's very hard to present the results of a Bayesian analysis in a way that fisheries managers can understand and make use of. Pikitch, Hilborn and McAllister can all remember times when their presentations left fisheries managers scratching their heads in confusion. "The decision is easier for them if a scientist tells them what to do and ignores the uncertainties," says McAllister.

But there are signs of progress. Fisheries scientists and managers alike are learning to

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use a technique called "decision analysis", a business tool for converting uncertain information into rational decisions. In 1998 the Pacific Fishery Management Council, which is responsible for managing stocks off California, Oregon and Washington, asked scientists to start presenting their Bayesian statistics in a decision analysis format. And in Europe, McAllister is preparing to use the format to present his Bayesian analysis of Baltic salmon to the ICES.

On the US Pacific coast, at least, the rockfish crash seems to have inspired scientists and managers to try new approaches. In the past four years, fisheries scientists have done a much better job of spelling out uncertainties, thanks in part to Bayesian statistics and decision analysis. Says Ralston: "If we had been able to present the uncertainties 10 years ago like we do now, the rockfish crash might not have developed as it did." ●

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