Towards sustainability in world fisheries

Daniel Pauly, Villy Christensen, Sylvie Guénette, Tony J. Pitcher, U. Rashid Sumaila, Carl J. Walters, R. Watson & Dirk Zeller

Fisheries Centre, University of British Columbia, 2204 Main Mall, Vancouver, British Columbia, Canada V6T 1Z4 (e-mail: d.pauly@fisheries.ubc.ca)

Fisheries have rarely been ‘sustainable’. Rather, fishing has induced serial depletions, long masked by improved technology, geographic expansion and exploitation of previously spurned species lower in the food web. With global catches declining since the late 1980s, continuation of present trends will lead to supply shortfall, for which aquaculture cannot be expected to compensate, and may well exacerbate. Reducing fishing capacity to appropriate levels will require strong reductions of subsidies. Zoning the oceans into unfished marine reserves and areas with limited levels of fishing effort would allow sustainable fisheries, based on resources embedded in functional, diverse ecosystems.

Fishing is the catching of aquatic wildlife, the equivalent of hunting bison, deer and rabbits on land. Thus, it is not surprising that industrial-scale fishing should generally not be sustainable: industrial-scale hunting, on land, would not be, either. What is surprising rather, is how entrenched the notion is that unspecified ‘environmental change’ caused, and continues to cause, the collapse of exploited fish populations. Examining the history of fishing and fisheries makes it abundantly clear that humans had for thousands of years a major impact on target species and their supporting ecosystems1. Indeed, the archaeological literature contains many examples of ancient human fishing associated with gradual shifts, through time, to smaller sizes and the serial depletion of species that we now recognize as the symptoms of overfishing2-2.

This literature supports the claim that, historically, fisheries have tended to be non-sustainable, although not unexpectedly there is a debate about the cause for this1, and the exceptions4. The few uncontested historical examples of sustainable fisheries seem to occur where a superabundance of fish supported small human populations in challenging climates3. Sustainability occurred where fish populations were naturally protected by having a large part of their distribution outside of the range of fishing operations. Hence, many large old fecund females, which contribute overwhelmingly to the egg production that renews fish populations, remained untouched. How important such females can be is illustrated by the example of a single ripe female red snapper, Lutjanus campechanus, of 61 cm and 12.5 kg, which contains the same number of eggs (9,300,000) as 212 females of 42 cm and 1.1 kg each6. Where such natural protection was absent, that is, where the entire population was accessible to fishing gears, depletion ensued, even if the gear used seemed inefficient in retrospect8-9. This was usually masked, however, by the availability of other species to target, leading to early instances of depletions observable in the changing size and species composition of fish remains, for example, in middens9.

The fishing process became industrialized in the early nineteenth century when English fishers started operating steam trawlers, soon rendered more effective by power winches and, after the First World War, diesel engines10. The aftermath of the Second World War added another ‘peace dividend’ to the industrialization of fishing: freezer trawlers, radar and acoustic fish finders. The fleets of the Northern Hemisphere were ready to take on the world.

Fishing science advanced over this time as well: the two world wars had shown that strongly exploited fish populations, such as those of the North Sea, would recover most, if not all, of their previous abundance when released from fishing5. This allowed the construction of models of single-species fish populations whose sizes is affected only by fishing pressure, expressed either as a fishing mortality rate (F), or catch/biomass ratio, or by a measure of fishing effort (f, for example, trawling hours per year) related to F through a catchability coefficient11,12 (q): F = qf. Here, q represents the fraction of a population caught by one unit of effort, directly expressing the effectiveness of a gear. Thus, q should be monitored as closely as fishing effort itself, if the impact of fishing on a given stock, as expressed by F, is to be evaluated. Technology changes tend to increase q, leading to increases referred to as ‘technology coefficient’14, which quickly renders meaningless any attempts to limit fishing mortality by limiting only fishing effort.

The conclusion of these models, still in use even now (although in greatly modified forms, Box 1), is that adjusting fishing effort to some optimum level should generate ‘maximum sustainable’ yield, a notion that the fishing industry and the regulatory agencies eagerly adopted — if only in theory15. In practice, optimum effort levels were very rarely implemented (the Pacific halibut fishery is one exception16). Rather the fisheries expanded their reach, both offshore, by fishing deeper waters and remote sea mounts17, and by moving onto the then untapped resources of West Africa18, southeast Asia19, and other low-latitude and Southern Hemispheric regions20.

Fisheries go global

In 1950, the newly founded Food and Agriculture Organization (FAO) of the United Nations began collection of global statistics. Fisheries in the early 1950s were at the onset of a period of extremely rapid growth, both in the Northern Hemisphere and along the coast of the countries of what is now known as the developing world. Everywhere that industrial-scale fishing (mainly trawling, but also purse seineing

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and long-line fishing) was introduced, it competed with small-scale, or artisanal fisheries. This is especially true for tropical shallow waters (10–100 m), where artisanal fisheries targeting food fish for local consumption, and trawlers targeting shrimps for export, and discarding the associated by-catch, compete for the same resource.

Throughout the 1950s and 1960s, this huge increase of global fishing effort led to an increase in catches (Fig. 1) so rapid that their trend exceeded human population growth, encouraging an entire generation of managers and politicians to believe that launching more boats would automatically lead to higher catches.

The first collapse with global repercussions was that of the Peruvian anchoveta in 1971–1972, which is often perceived as having been caused by an El Niño event. However, much of the available evidence, including actual catches (about 18 million tonnes) exceeding officially reported catches (12 million tonnes), suggest that overfishing was implicated as well. But attributing the collapse of the Peruvian anchoveta to ‘environmental effects’ allowed business as usual to continue and, in the mid-1970s, this led to the beginning of a decline in total catches from the North Atlantic. The declining trend accelerated in the late 1980s and early 1990s when most of the cod stocks off New England and eastern Canada collapsed, ending fishing traditions reaching back for centuries.

Despite these collapses, the global expansion of effort continued and trade in fish products intensified to the extent that they have now become some of the most globalized commodities, whose price increased much faster than the cost of living index. In 1996, FAO published a chronicle of global fisheries, showing that a rapidly increasing fraction of world catches originate from stocks that are depleted or collapsed, that is, ‘senescent’ in FAO’s parlance.

### Box 1

**Single-species stock assessments**

Single-species assessments have been performed since the early 1950s, when the founders of modern fisheries science attempted to equate the concept of sustainability with the notion of optimum fishing mortality, leading to some form of maximum sustainable yield. Most of these models, now much evolved from their original versions (some to baroque complexity, involving hundreds of free parameters), require catch-at-age data. Hence government laboratories, at least in developed countries, spend a large part of their budget on the routine acquisition and interpretation of catch and age-composition data.

Yet, single-species assessment models and the related policies have not served us particularly well, due to at least four broad problems. First, assessment results, although implying limitation on levels of fishing mortality which would have helped maintain stocks if implemented, have often been ignored, on the excuse that they were not ‘precise enough’ to use as evidence for economically painful restriction of fishing (the ‘burden of proof’ problem).

Second, the assessment methods have failed badly in a few important cases involving rapid stock declines, and in particular have led us to grossly underestimate the severity of the decline and the increasing (‘depensatory’) impacts of fishing during the decline.

Third, there has been insufficient attention in some cases to regulatory tactics: the assessments and models have provided reasonable overall targets for management (estimates of long-term sustainable harvest), but we have failed to implement and even develop effective short-term regulatory systems for achieving those targets.

Fourth, we have seen apparently severe violation of the assumptions usually made about ‘compensatory responses’ in recruitment to reduction in spawning population size. We have usually assumed that decreasing egg production will result in improving juvenile survival (compensation) so that recruitment (eggs × survival) will not fall off rapidly during a stock decline and will hence tend to stop the decline. Some stocks have shown recruitment failure after severe decline, possibly associated with changes in feeding interactions that are becoming known as ‘cultivation/depenensation’ effects. According to this phenomenon, adult predatory fish (such as cod) can control the abundance of potential predators and competitors of their juvenile offspring, but this control lost when these predatory fish become scarce. This may well lead to alternate stable states of ecosystems, which has severe implications for fisheries management.

Jointly, these four broad problems imply a need to complement our single-species assessments by elements drawn from ecology, that is, to move towards ecosystem-based management. What this will consist of is not clearly established, although it is likely that, while retaining single-species models at its core, it will have to explicitly include trophic interaction between species, habitat impacts of various gears, and a theory for dealing with the optimum placement and size of marine reserves (see main text). Ecosystem-based management will have to rely on the principles of, and lessons learnt from, single-species stock assessments, especially regarding the need to limit fishing mortality. It will certainly not be applicable in areas where effort or catch limits derived from single-species approaches cannot be implemented in the first place.

### Box 2

**Trophic levels as indicators of fisheries impacts**

There are many ways ecosystems can be described, for example in terms of the information that is exchanged as their components interact, or in terms of size spectra. But perhaps the most straightforward way to describe ecosystems is in terms of the feeding interactions among their component species, which can be done by studying their stomach contents. A vast historical database of such published studies exists, which has enabled a number of useful generalizations to be made for ecosystem-based management of fisheries. One of these is that marine systems have herbivores (zooplankton) that are usually much smaller than the first-order carnivores (small fish), which are themselves consumed by much larger piscivorous fishes, and so on. This is a significant difference from terrestrial systems, where, for example, wolves are smaller than the moose they prey on. Another generalization is that the organisms we have so far extracted from marine food webs have tended to play therein roles very different from those played by the terrestrial animals we consume. This can be shown in terms of their ‘trophic level’ (TL), defined as 1 + the mean TL of their prey.

Thus, in marine systems we have: algae at the bottom of the food web (TL = 1, by definition); herbivorous zooplankton feeding on the algae (TL = 2); large zooplankton or small fishes, feeding on the herbivorous zooplankton (TL = 3); large fishes (for example, cod, tuna and groupers) whose food tends to be a mixture of low- and high-TL organisms (TL = 3.5–4.5).

The mean TL of fisheries landings can be used as an index of sustainability in exploited marine ecosystems. Fisheries tend at first to remove large, slower-growing fishes, and thus reduce the mean TL of the fish remaining in an ecosystem. This eventually leads to declining trends of mean TL in the catches extracted from that ecosystem, a process now known as “fishing down marine food webs.”

Declining TL is an effect that occurs within species as well as between species. Most fishes are hatched as tiny larvae that feed on herbivorous zooplankton. At this stage they have a TL of about 3, but this value increases with size, especially in piscivorous species. Because fisheries tend to reduce the size of the fish in an exploited stock, they also reduce their TL.
Fisheries impact on ecosystem and biodiversity

The position within ecosystems of the fishes and invertebrates landed by fisheries can be expressed by their trophic levels, expressing the number of steps they are removed from the algae occupying a trophic level of 1 that fuel marine food webs (Box 2). Most food fishes have trophic levels ranging from 3.0 to 4.5, that is, from sardines feeding on zooplankton to large cod or tuna feeding on miscellaneous fish-trophic levels ranging from 3.0 to 4.5, that is, from sardines feeding on zooplankton to large cod or tuna feeding on miscellaneous fish. The principal, direct impact of fishing is that it reduces the number of steps they are removed from the algae occupying a trophic level of 1 that fuel marine food webs (Box 2). Most food fishes have trophic levels ranging from 3.0 to 4.5, that is, from sardines feeding on zooplankton to large cod or tuna feeding on miscellaneous fish-trophic levels ranging from 3.0 to 4.5, that is, from sardines feeding on zooplankton to large cod or tuna feeding on miscellaneous fish.

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form of fishing\textsuperscript{31}. Hence, given the extensive coverage of the world’s shelf ecosystems by bottom trawling\textsuperscript{50}, it is not surprising that generally longer-lived, demersal (bottom) fishes have tended to decline faster than shorter-lived, pelagic (open water) fishes, a trend also indicated by changes in the ratio of piscivorous (mainly demersal) to zooplanktivorous (mainly pelagic) fishes\textsuperscript{33}.

It is difficult to fully appreciate the extent of the changes to ecosystems that fishing has wrought, given shifting baselines as to what is considered a pristine ecosystem\textsuperscript{1,54} and continued reliance on single-species models (Box 1). These changes, often involving reductions of commercial fish biomasses to a few per cent of their pre-exploitation levels, prevent us taking much guidance from the concept of sustainability, understood as aiming to maintain what we have\textsuperscript{3,8}. Rather, the challenge is rebuilding the stocks in question.

**Reducing fishing capacity**

There is widespread awareness that increases in fishing-fleet capacity represent one of the main threats to the long-term survival of marine capture-fishery resources, and to the fisheries themselves\textsuperscript{55,56}. Reasons advanced for the overcapitalization of the world’s fisheries include: the open-access nature of many fisheries\textsuperscript{57}; common-pool fisheries that are managed non-cooperatively\textsuperscript{38,59}; sole-ownership fisheries with high discount rates and high price-to-cost ratios\textsuperscript{60}; the increasing replacement of small-scale fishing vessels with larger ones\textsuperscript{65}; and the payment of subsidies by governments to fishers\textsuperscript{61},\textsuperscript{63}, which generate ‘profits’ even when resources are overfished.

This literature shows that fishing overcapacity is likely to build up not only under open access\textsuperscript{64}, but also under all forms of property regimes. Subsidies, which amount to US$2.5 billion for the North Atlantic alone, exacerbate the problems arising from the open access and/or ‘common pool’ aspects of capture fisheries, including fisheries with full-fledged property rights\textsuperscript{61,63}.

Even subsidies used for vessel decommissioning schemes can have negative effects. In fact, decommissioning schemes can lead to the intended reduction in fleet size only if vessel owners are consistently caught by surprise by those offering this form of subsidy. As this is an unlikely proposition, decommissioning schemes often end up providing the collateral that banks require to underwrite fleet modernizations. Additionally, in most cases, it is not the actual vessel that is retired, but its licence. This means that ‘retired’ vessels can still be used to catch species without quota (so-called ‘under-utilized resources’, which are often the prey of species for which there is a quota), or deployed along the coast of some developing country, the access to which may also be subsidized\textsuperscript{63}. Clearly, the decommissioning schemes that will have to be implemented if we are ever to reduce overcapacity will have to address these deficiencies if they are not to end up, as most have so far, in fleet modernization and increased fishing mortality.

It is clear that a real, drastic reduction of overcapacity will have to occur if fisheries are to acquire some semblance of sustainability. The required reductions will have to be strong enough to reduce F by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in F, because catches can be maintained in the face of dwindling biomasses by increasing q (and hence F; see definitions above), even when nominal effort is constant. Indeed, this is the very reason behind the incessant technological innovation in fisheries, which now relies on global positioning systems and detailed maps of the sea bottom to seek out residual fish concentrations previously protected by rough terrain. This technological race, and the resulting increase in q, is also the reason why fishers often remain unaware of their own impacts on the resource they exploit and object so strongly to scientists’ claims of reductions in biomass.

If fleet reduction is done properly, it should result in an increase in net benefits (‘rent’) from the resources, as predicted by the basic theory of bioeconomics\textsuperscript{66}. This can be used, via taxation of the rent gained by the remaining fishers, to ease the transition of those who had to stop fishing. This would contrast with the present situation, where taxes from outside the fisheries sector are used, in form of subsidies, to maintain fishing at levels that are biologically unsustainable, and which ultimately lead to the depletion and collapse of the underlying resources.

**Biological constraints to fisheries and aquaculture**

Perhaps the strongest factor behind the politicians’ use of tax money to subsidize non-sustainable, even destructive fisheries, and its tacit support by the public at large, is the notion that, somehow, the oceans will yield what we need — just because we need it. Indeed,
The overwhelming majority of shelves are now ‘sheltered’ within the exclusive economic zones (EEZ) of maritime countries, which also include all coral reefs and their fisheries (Box 3). According to the 1982 United Nations Convention on the Law of the Sea, any country that cannot fully utilize the fisheries resource of its EEZ must make this surplus available to the fleet of other countries. This, along with eagerness for foreign exchange, political pressure and illegal fishing, has led to all of the world’s shelves being trawled for bottom fish, purse-seined for pelagic fishes and illuminated to attract and catch squid (to the extent that satellites can map the night-time location of fishing fleets as well as that of cities). Overall, about 35% of the primary production of the world’s shelves is required to sustain the fisheries, a figure similar to the human appropriation of terrestrial primary production.

The constraints to fisheries expansion that this implies, combined with the declining catches alluded to above, have led to suggestions that aquaculture should be able to bridge the gap between supply and demand. Indeed, the impressive recent growth of reported aquaculture is often cited as evidence of the potential of that sector to meet the growing demand for fish, or even to ‘feed the world’.

Three lines of argument suggest that this is unlikely. The first is that the rapidly growing global production figures underlying this documented growth are driven to a large extent by the People’s Republic of China, which reported 63% of world aquaculture production in 1998. But it is now known that China not only over-reports its marine fisheries catches, but also the production of many other sectors of its economy. Thus, there is no reason to believe that global aquaculture production in the past decades has risen as much as officially reported.

Second, modern aquaculture practices are largely unsustainable: they consume natural resources at a high rate and, because of their intensity, they are extremely vulnerable to the pollution and disease outbreaks they induce. Thus, shrimp aquaculture ventures are in many cases operated as slash-and-burn operations, leaving devastated coastal habitats and human communities in their wake.

Third, much of what is described as aquaculture, at least in Europe, North America and other parts of the developed world, consists of feedlot operations in which carnivorous fish (mainly salmon, but also various sea bass and other species) are fattened on a diet rich in fish meal and oil. The idea makes commercial sense, as the farmed fish fetch a much higher market price than the fish ground up for fish meal (even though they may consist of species that are consumed by people, such as herring, sardine or mackerel, forming the bulk of the pelagic fishes in Fig 1). The point is that operations of this type, which are directed to wealthy consumers, use up much more fish flesh than they produce, and hence cannot replace capture fisheries, especially in developing countries, where very few can afford imported smoked salmon. Indeed, this form of aquaculture represents another source of pressure on wild fish populations.

**Perspectives**

We believe the concept of sustainability upon which much quantitative fisheries management is based to be flawed, because there is a little point in sustaining stocks whose biomass is but a small fraction of its value at the onset of industrial-scale fishing. Rebuilding of marine systems is needed, and we foresee a practical restoration ecology for the oceans that can take place alongside the extraction of marine resources for human food. Reconciling these apparently dissonant goals provides a major challenge for fisheries ecologists, for the public, for management agencies and for the fishing industry. It is important here to realize that there is no reason to expect marine resources to keep pace with the demand that will result from our growing population, and hopefully, growing incomes in now impoverished parts of the world, although we note that fisheries designed to be sustainable in a world of scarcity may be profitable.

We argued in the beginning of this review that whatever semblance of sustainability fisheries in the past might have had was due...
to their inability to cover the entire range inhabited by the wildlife species that were exploited, which thus had natural reserves. We further argued that the models used traditionally to assess fisheries, and to set catch limits, tend to require explicit knowledge on stock status and total withdrawal from stocks, that is, knowledge that will inherently remain imprecise and error prone. We also showed that generally overcapitalized fisheries are leading, globally, to the gradual elimination of large, long-lived fishes from marine ecosystems, and their replacement by shorter-lived fishes and invertebrates, operating within food webs that are much simplified and lack their former ‘buffering’ capacity.

If these trends are to be reversed, a huge reduction of fishing effort involving effective decommissioning of a large fraction of the world’s fishing fleet will have to be implemented, along with fisheries regulations incorporating a strong form of the precautionary principle. The conceptual elements required for this are in place, for example, in form of the FAO Code of Conduct for Responsible Fisheries, but the required political will has been lacking so far, an absence that is becoming more glaring as increasing numbers of fish populations and eventually fish species will become extinct. Fluctuations or climate change (Fig. 3). Moreover, many exploited marine protected areas (MPAs), with no-take reserves at their core, have been shown to have positive effects in helping to prevent overexploitation by setting an upper limit on fishing mortality. Marine protected areas are particularly important in the absence of explicit fishery regulations, as these collapses will be attributed to environmental fluctuations or climate change (Fig. 3). Moreover, many exploited fish populations and eventually fish species will become extinct. MPAs that cover a representative set of marine habitats should help prevent this, just like forest and other natural terrestrial habitats have enabled the survival of wildlife species which agriculture would have otherwise rendered extinct.

Focused studies on the appropriate size and location of marine reserves and their combination into networks, given locale-specific oceanographic conditions, should therefore be supported. This will lead to the identification of reserve designs that would optimize export to adjacent fished areas, and which could thus be offered to the affected coastal and fisher communities, whose consent and support will be required to establish marine reserves and restructure the fisheries. The general public could also be involved, through eco-labeling and other market-driven schemes, and through support for conservation-oriented non-governmental organizations, which can complement the activities of governmental regulatory agencies.

In conclusion, we think that the restoration of marine ecosystems to some state that existed in the past is a logical policy goal. There is still time to achieve this, and for our fisheries to be on a path towards sustainability.
