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 have had for thousands of years a major impact on target species and their supporting ecosystems. 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 overfishing.

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 this, and the exceptions. The few uncontested historical examples of sustainable fisheries seem to occur where a superabundance of fish supported small human populations in challenging climates. Sustainability occurred where fish populations were naturally protected by having a large part to 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 each. Where such natural protection was absent, that is, where the entire population was accessible to fishing gears, depletion ensued, even if the gear used seems inefficient in retrospect. 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 middens.

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 engines. 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.

Fisheries 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 fishing. This allowed the construction of models of single-species fish populations whose size 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 coefficient (q). 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', 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 theory. In practice, optimum effort levels were very rarely implemented (the Pacific halibut fishery is one exception). Rather the fisheries expanded their reach, both offshore, by fishing deeper waters and remote sea mounts, and by moving onto the then untapped resources of West Africa, southeast Asia, and other low-latitude and Southern Hemispheric regions.

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
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 of New England and eastern Canada collapsed, ending fishing traditions reaching back for centuries.

Despite these collapses, the global expansion of effort continued and tradefish 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. Yet,
global catches seemed to continue, increasing through the 1990s according to official catch statistics. This surprising result was explained recently when massive over-reporting of marine fisheries catches by one single country, the People’s Republic of China, was uncovered. Correcting for this showed that reported world fisheries landings have in fact been declining slowly since the late 1980s, by about 0.7 million tonnes per year.

Fisheries impact on ecosystem and biodiversity

The position within ecosystems of the fishes and invertebrates land by fisheries can be expressed by their trophic levels, expressing the number of steps they are removed from the algal (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 fishes. Thus, the observed global decline of 0.05–0.10 trophic levels per decade in global fisheries landings (Fig. 2) is extremely worrisome, as it implies the gradual removal of large, long-lived fishes from the ecosystems of the world oceans. This is perhaps most clearly illustrated by a recent study in the North Atlantic showing that the biomass of large and slow to mature, have limited geographical range, and/or have sporadic recruitment. There is actually little support, though, for the general assumption that the most highly fecund marine fish species are less susceptible to overexploitation; rather it seems that this perception is flawed. Fisheries may also change the evolutionary characteristics of populations by selectively removing the larger, fast-growing individuals, and one important research question is whether this induces irreversible changes in the gene pool. Overall, this has implications for research, monitoring and management, and it points to the need for incorporating ecological consideration in fisheries management.

Another worrisome aspect of fishing down marine food webs is that it involves a reduction of the number and length of pathways linking food fishes to the primary producers, and hence simplification of the food webs. Diversified food webs allow predators to switch between prey as their abundance fluctuates, and hence to compensate for prey fluctuations induced by environmental fluctuations. Fisheries-induced food-web simplification, combined with the drastic fisheries-induced reduction in the number of year classes in predator populations, makes their reduced biomass strongly dependent of annual recruitment. This leads to increasing variability, and to lack of predictability in population sizes, and hence in predicted catches. The net effect is that it will increasingly look like environmental fluctuations impact strongly on fisheries resources, even where they originally did not. This resolves, if in a perverse way, the question of the relative importance of fisheries and environmental variability as the major driver for changes in the abundance of fisheries resources (Fig. 3).

It seems unbelievable in retrospect, but there was a time when it was believed that bottom trawling had little detrimental impact, or a beneficial impact, on the sea bottom that it ‘ploughed’. Recent research shows that the ploughing analogy is inappropriate and that, if an analogy is required, it should be that of clear cutting forests in the course of hunting deer. Indeed, the productivity of the benthic organisms at the base of food webs leading to food fishes is seriously impacted by bottom trawling, as is the survival of their juveniles when deprived of the biogenic bottom structure destroyed by that
form of fishing\textsuperscript{53}. Hence, given the extensive coverage of the world’s shelf ecosystems by bottom trawling\textsuperscript{38}, it is not surprising that generally longer-lived, demersal (bottom) fishes tend 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{39}.

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{15,44} 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{20,38}. 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{26,59}; sole-ownership fisheries with high discount rates and/or high price-to-cost ratios\textsuperscript{48}; the increasing replacement of small-scale fishing vessels with larger ones\textsuperscript{54}; and the payment of subsidies by governments to fishers\textsuperscript{59}, 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{66}, 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{17,61}.

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 collaterals 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{57}. 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 fishing capacity by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing mortality. The required reductions will have to be strong enough to reduce fishing effort by a factor of two or three in some areas, and even more in others. This must involve even greater decreases in fishing effort, if because catches can be maintained in the face of dwindling biomasses by increasing fishing efficiency.
demand projections generated by national and international agencies largely reflect present consumption patterns, which by some measures the oceans ought to help us maintain, even if the global human population were to double again. Although much of the deep ocean is indeed unexplored and 'mysterious', we know enough about ocean processes to realise that its productive capacity cannot keep up with an ever-increasing demand for fish.

Just as a tropical scientist might look at the impressive expanse of Canada and assume that this country has boundless potential for agricultural production, unaware that in reality only the thin sliver of land along its southern border (5%) is arable, we terrestrial aliens have assumed that the expanse and depths of the world's oceans will provide for us in the ways that its more familiar coastal fringes have. But this assumption is very wrong. Of the 363 million square kilometres of ocean on this planet, less than 7% — the continental shelves — are shallower than 200 m, and some of this shelf area is covered by ice. Shelves generate the biological production supporting over 90% of global fish catches, the rest consisting of tuna and other oceanic organisms that gather their food from the vast, desert-like expanse of the open oceans.

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 on the world's shelves is required to sustain the fisheries, a figure similar to the human appropriation of terrrestrial 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. This means 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 most quantitative fisheries management is based to be flawed, because there is 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 realise 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, which 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 forms 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 fisheries collapse throughout the world, and catches continue to decline.

Given the high level of uncertainty facing the management of fisheries, which induced several collapses, it has been suggested by numerous authors that closing a part of the fishing grounds would prevent overexploitation by setting an upper limit on fishing mortality. Marine protected areas (MPAs), with no-take reserves at their core, combined with a strongly limited effort in the remaining fishable areas, have been shown to have positive effects in helping to rebuild depleted stocks19–27. In most cases, the successful MPAs used to protect rather sedentary species, rebuild their biomass, and eventually sustain the fishery outside the reserves by exporting juveniles or adults28. Although migrating species would not benefit from the local reduction in fishing mortality caused by an MPA, the MPA would still help some of these species by reducing the complexity of their habitat destroyed by trawling, and thus decrease mortality of their juveniles29. Enforcement of the no-take zones within MPAs would benefit from the application of high technology (for example, satellite monitoring of fishing vessels), presently used mainly to increase fishing pressure.

There is still much fear among fisheries scientists, especially in extra-tropical areas, that the export of fish from such reserves would not be sufficient to compensate for the loss of fishing ground30. Although we agree that marine reserves are no panacea, the present trends in fisheries, combined with the low degree of protection presently afforded (only 0.01% of the world’s ocean is effectively protected), virtually guarantee that more fish stocks will collapse, and that 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 subset of marine habitats should help prevent this, just like forest and other terrestrial habitats have enabled the survival of wildlife species which agriculture would have otherwise rendered extinct.

Focus 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-labelling and other market-driven schemes, and through support for conservation-oriented non-government 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 goal32. There is still time to achieve this, and for our fisheries to be on a path towards sustainability.


