Sustainability of Fisheries

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1. Introduction

In this paper I shall investigate the concept of sustainability as it applies to fisheries. In fact, the concept of "sustainable yield" is a time-honored one in fisheries science. Its application is, however, more complicated than simple, deterministic fishery models might lead one to believe. While useful pedagogical devices, such models have the potential to mislead if instead they are applied to contexts in which environmental fluctuations unrelated to fishing effort play a major role in determining fish stocks and fish catches. As is shown below, the catches from and abundance of stocks subject to environmental fluctuations vary over time, sometimes formidably. Yet the exploitation of such stocks can be sustainable, in the sense that the stocks survive and sustain ongoing exploitation. In fact sustainable exploitation of such stocks is likely to imply a variable rate of exploitation, one that is adjusted to the conditions at each time. But unless such adjustment is timely and prudent, the results could be disastrous. There are several cases of stock collapses on record, although few appear irreversible.

What, then, prevents a timely and prudent adjustment? Sometimes collapses have occurred despite a declared objective of conservative exploitation. Sometimes recent advances in technology coupled with adverse environmental conditions have led to collapses. And sometimes the experience probably was insufficient for identify looming threats and how to respond to them. Finally, sustainable exploitation could lose its relevance, because of changing needs and perceptions.

As a useful background, I shall begin (next section) with some critical remarks about the concept of sustainability in a general economic context. This is followed (Section 3) by a bare bones outline of the deterministic fisheries model, in order to show that even in this very simple context, the concept of sustainability alone does not lead us very far towards deciding what particular fishing strategy to apply. In Section 4, I introduce environmental fluctuations, looking at the Northeast-Arctic cod over the past one hundred years. The fisheries exploiting this stock are still alive and thriving, indicating the possibility of sustainability against considerable odds. Section 5 considers four serious cases of fishery collapses, each offering its own lessons as well as highlighting the relative importance of environmental and institutional factors. Finally, I draw on the foregoing analysis to consider the institutional arrangements that promote sustainable fisheries.

2. Sustainable development: some critical issues

The coining of the phrase "sustainable development" must be considered a major success. Few phrases ring more often in our ears. It has given rise to a voluminous literature on what it means -- a literature that is still growing, which suggests that it is perhaps a greater success from the point of view of sloganeering than of clarity. Quite often, people seem to use it for things that for want of a better term might be described as "great and good", whether or not they have anything to do with development, sustainable or otherwise.

Not all of the blame for this should be laid at the threshold of the initiators of the concept; much of it rests with muddled thinking by those who have found sustainable development a convenient phrase. The definition given by the Brundtland Commission, "development that meets the needs of the present without compromising the ability of future generations to meet their own needs," (WCED 1987, 8) was undoubtedly well-intended, and one can understand its appeal. Compromising the future of one's children through profligacy has never been regarded as an honorable behavior.

The problem with "sustainable development" lies in giving it precise meaning and making it operational. Is "sustainable" something that is repeated over and over again without any change? What, then, happened to development? And if change takes place, what, then, is sustained? Here the many who have tried to breathe some meaning into the famous phrase have offered various proposals. The most intuitively appealing proposal is, perhaps, that consumption per capita should never fall.

But consumption is a many-dimensional thing. In a growing economy where technology is constantly changing and new gadgets and services are continuously being developed, it is not straightforward to find a one-dimensional expression for consumption. Leaving such nitpicking aside, the bigger message is that in a growing economy with technological change, satisfying the "needs" of any generation is a process that is constantly evolving.

Even the definition of "needs" is liable to change over time and space. What some regard as "needs" in rich countries today were aspirations hardly anyone had imagined a hundred years ago. Is provision of safe drinking water a "need"? In the cities of the industrial revolution it was not available. Hundreds of millions of people still do not have that need satisfied even today. Is access to medical services a "need"? Most of the medical technologies we take for granted in rich countries today did not exist a hundred years ago, and even now they are not available to the poorest people of the world.

Our Common Future, the report that spawned the notion of sustainable development, arose partly because of worries that non-renewable natural resources are finite and perhaps overused (WCED 1987, 6). But no use whatever of such resources can be characterized as sustainable in the truly long term. If they are to be used at all, then, sustainability can only be achieved by substituting other resources (including human resources and "renewable" resources). If we look back in history, we see just that: one process or resource is replaced by another (whale oil was replaced by crude oil; the internal combustion engine replaced horses; email has to some degree replaced snail mail; mp3s are replacing CDs, which replaced vinyl records; etc.), and at the same time living standards have continued to improve. Given that, one may wonder how it was that the instigators of the World Commission on Environment and Development ever got the idea that sustainability of the modern industrial civilization is a problem.

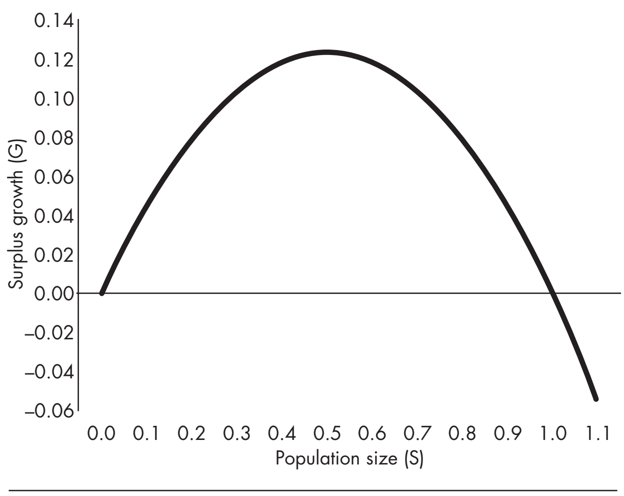
Narrowing the focus from sustainable development in the world as a whole or some part thereof to one particular sector, in this case fisheries, simplifies the problem a great deal. We are much less troubled by multi-dimensional outputs, and there are in general far fewer variables to be handled. In fact, ever since fisheries science began to develop over a hundred years ago, one of its basic concepts has been sustainable yield of fish stocks (Smith 1994). But even here, as we shall see, defining sustainable yield and making it operational is not without problems. There is enormous natural variability to be reckoned with. There is also technological progress. And there is change in human values that affect the relevance of sustainable yield from a particular fish stock or its trade-off vis-à-vis other goods.

3. Sustainable fisheries in a deterministic world

Fish stocks are renewable resources. If left alone, the oceans do not fill up entirely with fish, so one may surmise that there is some kind of a "natural equilibrium" in which growth is balanced by deaths. Many of the world's fish stocks have been exploited since time immemorial and are still around. Since fishing reduces stocks below their natural equilibrium, it may be concluded that catching fish results in surplus growth in excess of natural deaths, and so fishing at some level can be continued indefinitely without destroying the fishery.

But no fish generate no fish, and small fish stocks are perhaps not self-sustaining. Indeed, the surplus growth of fish stocks can be thought of as a rising function of the stock size, beginning at some low level (perhaps zero), rising up to a certain point, falling to zero again at the natural equilibrium, and then becoming negative – so that any stock size greater than the natural equilibrium automatically tends to fall back to that level. Figure 1 shows such a curve generated by the famous logistic

Figure 1 **Surplus growth (*G*) of a fish stock (*S*) generated by the logistic growth function $G(S) = rS(1 - S/K)$ with $r = 0.5$ and $K = 1$.**



growth model. (The main attraction of that model is mathematical convenience, but it captures adequately the hypothesized hump shape of the stock growth curve.)

A basic proposition that follows from this simple model is that if fishing never exceeds the surplus growth of fish, it could be sustained indefinitely. The stock could be held in an equilibrium below the natural one (where the curve intersects the stock-axis from above and left), provided the deaths caused by fishing exactly match the surplus growth (growth in excess of natural deaths). But the concept of sustainability alone does not get us very far. As Figure 1 demonstrates, there is a wide range of sustainable yields to choose from, from zero to the maximum. And associated with each particular sustainable yield, except the maximal one, are two different levels of the fish stock; we can take any particular sustainable yield from either a "small" or a "large" stock.

The reader is perhaps tempted to conclude that it would be better to take any given sustainable yield from a large stock, because a large stock would be more resilient to any environmental catastrophe that might occur. But this would take us beyond the deterministic world underlying the surplus growth function in Figure 1 and would pose a whole new set of problems for the sustainability concept, which we shall address below. There are, however, economic arguments which would make the larger of the two stock levels more attractive; for example, it is probably cheaper to catch any given amount of fish from a large stock than from a small stock.

But economic arguments can pull both ways. Suppose the cost per unit of fish landed is unrelated to the size of stock being exploited. It would not matter, then, whether we take any given sustainable yield from a large or a small stock. In fact, there would be an advantage in taking it from the smaller stock. Fishing down the stock to the smaller of the two levels would give us a once and for all gain (in the form of a larger initial yield), but once we are at our desired sustainable yield, we would catch the same amount that we would have obtained from the larger stock.

More generally, there is a trade-off between the once and for all gain we can realize by fishing down the stock and the loss we would incur by taking the sustainable yield from a smaller stock than necessary. Unsurprisingly, this trade-off is affected by the discount rate: if the discount rate is higher than the highest possible return on the fish stock, it would make sense to deplete the stock and invest the profit in a more productive asset.[1] Those who balk at such a conclusion can seek comfort in the possibility that if the stock has a value as such, for environmental reasons for example, it might not be a good idea to deplete it beyond repair. But the example serves to point out that it is the negligible rate of growth that makes utilization of non-renewable resources unsustainable (no matter how desirable their use may be) and that the distinction between sustainable and non-sustainable use of resources is a question of the rate of return on deferred use and not of zero versus positive rate of growth, however small.

4. Sustainability in a variable environment

The surplus growth curve in Figure 1 assumes a fully deterministic world, the growth of the fish being fully determined by the size of the stock. By choosing the level of fishing, we can fully control the fish stock and its surplus growth. This is a gross and in many cases misleading simplification. The growth of fish stocks is affected by environmental conditions that have nothing to do with fishing; sometimes these conditions even dwarf the effects of fishing and make them very difficult to identify. In fact, up to the late 19th century it was received wisdom among the most prominent biologists of the world that fishing had a negligible effect on the growth of fish stocks and that the fish resources of the oceans were for all practical purposes inexhaustible (Smith 1994). This received wisdom has long since been thoroughly discredited, and the surplus growth curve in Figure 1 and similar constructions are useful pedagogical devices to drive home the point that fish resources are limited and must be exploited with due care for the future consequences. But anyone intending to use such models for taking real world decisions about how much to fish in any particular season will be disappointed. When environmental conditions are good, we are likely to be able to take more than otherwise without doing much harm to future fishing. And what if fish stocks are subject to recurring environmental catastrophes which can neither be controlled nor predicted? Would it not then be sensible to catch the fish while they are still around, since they might be gone tomorrow? I shall revisit that question in the next section.

Let me illustrate, first, the point about variability by considering the case of the Northeast Arctic cod, one of the fish stocks for which we have the longest time series. Figure 2 shows the catches from and the biomass of this stock. There is enormous inter-annual variability in both. The trends are in opposite directions; while the stock has trended downwards, the catches have trended upwards, reflecting increasing pressure from the fishing industry. Nevertheless the catches follow the variations in the stock size rather closely. For the period after 1976 this is in part a consequence of the fact that the stock has been managed by an overall catch quota set on the basis of the abundance of the stock, although there has been substantial fishing above quota and some unregulated fishing as well. But even before 1977 there is a close relationship between the catches and the size of the stock. The reason is that the larger the stock, the more fish any given fishing effort is likely to catch. Because of this there is also likely to be less fishing activity if the stock is small than when it is abundant.

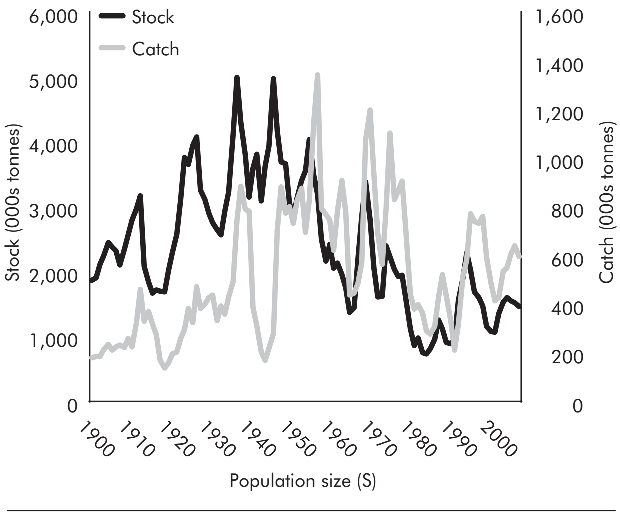
The stock fluctuations are largely driven by variability in the recruitment of young fish. Figure 3 shows the recruitment of 3-year old fish to the stock since 1913. The largest year classes of fish are more than an order of magnitude greater than the smallest ones. It has not proven easy to relate these fluctuations to variations in the mature part of the stock; they seem to be driven by variations in the environment. As Figure 3 shows, very large year classes occur at somewhat irregular intervals, with the period 1945–1975 being somewhat exceptional in having some extraordinarily large year classes. One might be tempted to conclude that some kind of regime shift occurred in the ocean some time after 1970, but in fact it is possible to produce a similar pattern by purely random fluctuations coupled with a simple serial correlation (Hannesson 2007).

Despite these fluctuations, the Northeast Arctic cod fishery has turned out to be sustainable in the sense that the stock is still around (even if it is smaller than it was before the mid-1970s) and since 1990 has been trending upwards rather than downwards. The fishery is also thriving, even if the volume of catches has declined since the 1950s and 60s. Since the fishery was essentially unregulated before 1977, this may be regarded as fortuitous. Since 1977 the fishery has been regulated by an overall quota. Although the quota has often been exceeded, sometimes on a large scale, it is likely to have contributed to preserving the fishery in a viable state.

Note that the catches in this fishery have varied a great deal. Since 1977, this variability has been managed under the quota regime, with the overall quota being adapted to the conditions of the stock at particular points in time. In general – and notwithstanding the breaches of the quota – the variation in catch has broadly been desirable, in that it has promoted continued sustainability of the fishery.

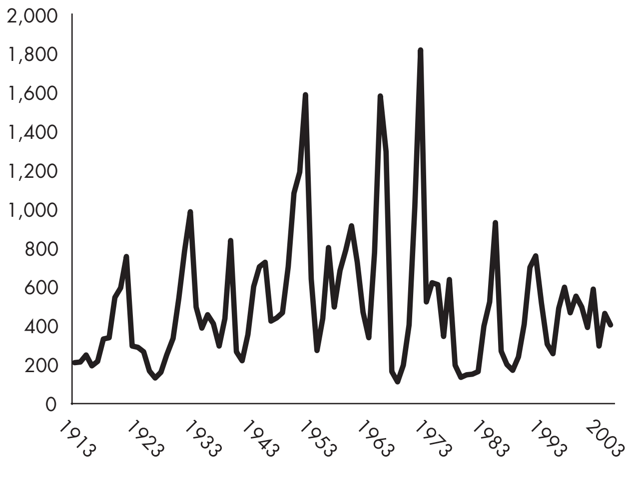
More generally, environment-driven fluctuations, such as the ones characterizing the Northeast Arctic cod, force us to ask ourselves how such fluctuations might be best dealt with. Sustainable exploitation in this context means preserving the stock and the fishery in a viable state for an indefinite period of time, but it is highly likely to also mean adapting the annual catch volume and the activity and capacity of the fishing fleet to the condition of the stock at each particular time. Declining catch volumes and stock levels do not necessarily indicate unsustainable exploitation; on the contrary this could be a warranted adjustment to adverse conditions in the environment. It might be feasible to stabilize the annual catch from this

Figure 2 **Catches (includes estimated unreported catches) from and stock size of the Northeast Arctic cod**



Sources: ICES, Arctic Working Group Report 2007, Table 3.27, and Institute of Marine Research, Bergen

Figure 3 **Recruitment of 3-year old fish to the Northeast Arctic cod stock**
Million fish



Sources: ICES, Arctic Working Group Report 2007, Table 3.27, and Institute of Marine Research, Bergen and other similar stocks, but such stabilization could mean an unreasonably small catch, since stabilizing the catch would mean a relatively intense exploitation of a small stock, making it more vulnerable (Hannesson and Steinshamn 1990).

5. Fishery collapses

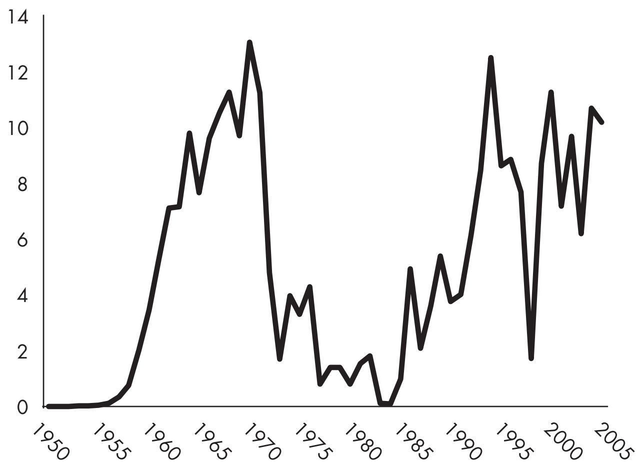
Some fisheries have developed very differently from the fishery for the Northeast Arctic cod and collapsed. Figures 4–7 track these sad stories (which are not the only ones of their kind). Common to all four is a sudden and unexpected collapse. Three of these fisheries have recovered, after a prolonged period in the doldrums. In all four cases both environmental conditions and overfishing were involved, but to different degrees. While the reasons for these collapses may still be subject to debate, they clearly pose different challenges with respect to sustainable fishing.

The collapse of the Peruvian anchovy fishery occurred after about a decade of rapid expansion, during which the fishery became a significant player in the Peruvian economy. The collapse in 1972 came during an El Niño, an event which is harmful for the growth and recruitment of the anchovy. It was long known that El Niños come at irregular intervals, but their portents for the anchovy fishery had not yet been learnt; the fishery was not reined back in a timely fashion, the anchovy stock was fished down and took 20 years to recover fully. The contrast with 1997 is striking. That year was also an El Niño year, but the fishery was severely curtailed, and the fish stock recovered after only one year. Since then, catches have varied, due to variable environmental conditions, but a collapse has been avoided.[2]

The Atlanto-Scandian herring fishery collapsed suddenly in the late 1960s.[3] There is little doubt that the main reason was a sudden improvement in technology coupled with the absence of any overall regulation. Two kinds of technological change were involved. Mechanical winches replaced brute manpower in hauling the gear with which the fish were caught, making it possible to use much bigger seines and boats. Secondly, sonar made it possible to search for fish under water in all directions and locate the shoals of fish. The fish no longer found refuge in the depth and darkness of the sea, and the last herring shoal might very well have been swept up if the fishery had not been stopped in the early 1970s. It took over 20 years for the fishery to recover. What complicates the story is that the 1960s were a cold period in the Northeast Atlantic. It has been shown that herring catches have a long-term correlation with temperature in this area, so some decline of the herring fishery could have been expected in any case (Toresen and Østvedt 2000). Throughout history herring catches have always fluctuated, undoubtedly for environmental reasons that still are not fully understood.

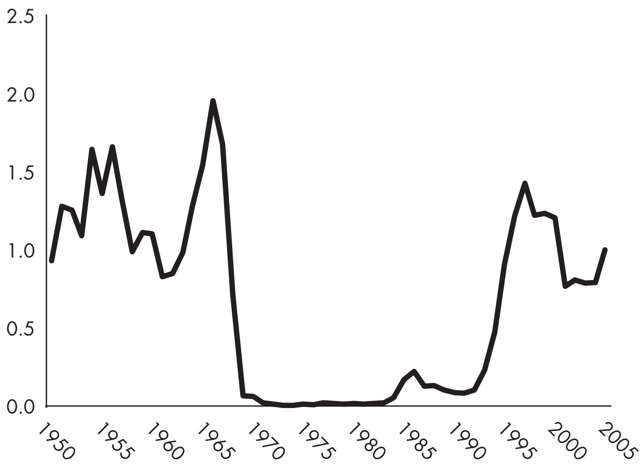
The catches of the California sardine declined steeply after 1950, and in the 1960s the fishery was banned. The fish stock recovered in the 1980s, and in the 1990s the ban

Figure 4 **Catches of Peruvian anchovy**
Million tonnes



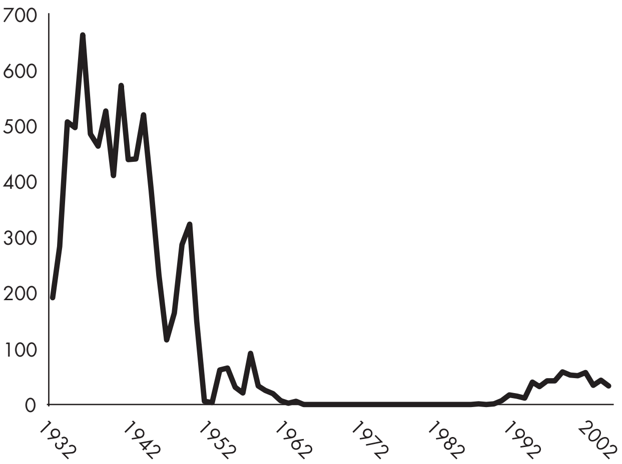
Source: FAO Fisheries Database

Figure 5 **Catches of Atlanto-Scandian herring**
Million tonnes



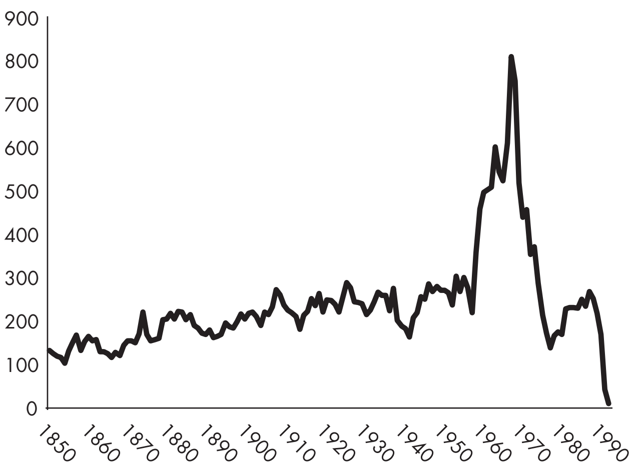
Sources: ICES, Northern Pelagic and Blue Whiting Working Group Report 2006, Table 3.5.2.1 and Institute of Marine Research, Bergen

Figure 6 **Catches (California) of California sardine**
Thousand tonnes



Source: NOAA Southwest Fisheries Center, La Jolla

Figure 7 **Catches of the Northern cod of Newfoundland**
Thousand tonnes



Source: Dr. Ram Meyers, Canada Fisheries and Oceans, Newfoundland laboratory

on catches was lifted. The sardine catches are nowhere near the levels of their heydays in the 1930s and 40s, partly because the processing industry that turned sardines into meal and oil is long gone. In fact the anchovy fishery of Peru and similar fisheries elsewhere developed partly because of the disappearance of the California sardine and the resulting effect on the supply of fish meal (Glantz 1992).

Initially the collapse of the sardine fishery was blamed on overfishing. This was challenged by results from drilling into sediments off the coast of California. These results showed that the frequency of sardine scales in the sediments varied greatly over time, long before any fishery for sardines had developed, indicating that the sardine stock had varied in the past for reasons that have nothing to do with fishing (Baumgartner, Soutar and Ferreira-Bartrina 1992). Presumably these collapses in the past were caused by environmental fluctuations. Later analyses have shown that the recruitment to the sardine stock is adversely affected if ocean temperatures diverge from a certain interval that apparently is advantageous for sardine survival (Jacobson et al. 2005).

This finding challenges the paradigm of sustainability. If a fish stock is doomed to disappear as a commercially interesting venture, are we not better off, then, taking more than we would otherwise? The prospects for future growth might be rendered null and void by adverse environmental changes over which we have no control, frustrating our attempts to improve our future fishery. A formal analysis of this problem, taking into account that a stock might collapse with a certain probability, shows that we should fish more and set aside less in this case than we otherwise would (Johnston and Sutinen 1996).

The Northern cod of Newfoundland is perhaps the most troublesome story of the four. Newfoundland's raison d'être as a part of the British Empire was its rich cod fishery, which continued uninterrupted through recorded history, notwithstanding some inter-annual fluctuations that characterize almost all fish stocks. In the 1960s, the catches from this stock reached unprecedented heights, due to the arrival of factory trawlers from the Soviet Union and other communist countries. The impressive fishing power of these vessels and fears that they would deplete the fish stocks were an important driving force behind the new law of the sea, which in the 1970s awarded jurisdiction over natural resources, including fish, to the nearest coastal state, up to a distance of 200 nautical miles from shore.

The new law of the sea put most of the area inhabited by the Northern cod under Canadian jurisdiction. While foreign fishing vessels were banished from the area, the Canadian fishing fleet expanded formidably. A limit was set on the catches and, as a result, they went down substantially, but not sufficiently to conserve the stock. The total catch was supposed to be set on the basis of a conservative criterion (the so-called $F_{0.1}$ criterion), but apparently the Canadian scientists seriously misjudged the size of the stock and the fishing mortality to which it had been subjected (Alverson 1987; Harris 1990; Hutchings and Meyers 1994). Environmental and technological factors also played a role in the decline of the stock; lower ocean temperatures adversely affected the growth of the stock and led to its aggregation in warm water pockets, where it was promptly found by trawlers equipped with modern fish finding devices, scooping up virtually the last remains of the stock. In 1992, the fishery was closed and has since only been reopened sporadically on an experimental basis. To date, the stock has not yet recovered to an extent that would allow a regular fishery.

The Northern cod debacle is that much more deplorable as Canada has some of the best fisheries scientists in the world and intended to manage the stock conservatively. Yet it failed miserably. It is implausible that the Canadian government should have deliberately permitted the stock to be fished out for some political expediency; as it turned out, the economic problems accompanying the collapse quickly hit the Canadian government right in the face. The Canadian government can, however, be criticized for not cutting the catches sufficiently and soon enough. For many years the fishing industry of Newfoundland had been regarded as a means of keeping people employed in the province, irrespective of their contribution to the Canadian economy. The industry was subsidized to such an extent that it can be doubted whether its contribution to the overall economy of the country was in fact positive (Schrank et al. 1995). The political fallout from severe cuts in catches and the accompanying increases in unemployment made the Canadian government reluctant to take sufficiently timely and severe measures as the Northern cod debacle unfolded, but it ended up with a much worse problem.

A possible contributing factor to the Northern cod debacle is the fact that the stock was not fully confined to the Canadian economic jurisdiction. Parts of the Grand Banks of Newfoundland are outside the 200-mile economic zone and accessible by fishing fleets from other countries. Foreign fleets, especially from Spain and Portugal, fished the Northern cod in this area, and for years the European Union ignored Canadian requests to reduce its fishing and set conservative quotas.[4]

6. Which institutional arrangements promote sustainability?

Until the new law of the sea emerged in the 1970s, most fish stocks were common property resources which anyone could access at will. The fate of such resources is well known. It was popularized by Hardin's famous article (Hardin 1968) about the tragedy of the commons, but the basic theory had been developed much earlier in the context of fisheries (Gordon 1954; Warming 1911, translated and introduced to the international community by Andersen (1983)). There is every reason to expect sustainable exploitation of common property resources to be the exception rather than the rule, especially if the "community" is large and its limits ill-defined. We have seen resource depletion being played out over a very short period of time for many terrestrial animals, such as the American bison (Buffalo Bill killed more than four thousand of them in eight months to feed construction workers on the Union Pacific Railroad).[5] But even the primitive technology of stone-age man permitted him to kill off many species of large animals which were easily found and hunted (Smith 1975, Diamond 2005). Why most of the fish stocks of the world have been exploited sustainably, in the sense that they are still around and supporting fisheries, is due to the difficulty of finding the last fish, or more precisely of reducing fish stocks below levels at which they can reproduce and grow.

In the last century, fishing technology grew by leaps and bounds, making it possible to reduce fish stocks below critical levels of viability. This led to a scramble for extended jurisdiction over fisheries and other resources at sea. The coastal states of the world, some of which owed much of their living standards to the fish resources off their shores, were in no mood to let fishing fleets from distant nations destroy their livelihoods.

As the leading powers of the world at the time, the United States and the Soviet Union, concurred in the extension of national jurisdiction over the sea (if for their own reasons), this aspiration made its way into international law. The establishment of national jurisdiction over fish stocks to a significant degree ensured that they were not destroyed through unfettered access by fishing fleets employing the latest technologies. However, the Northern cod debacle shows that national jurisdiction over fish stocks may be a necessary condition, but it is not a sufficient condition for their sustainable use.

For many fish stocks, the 200-mile zone does not establish jurisdiction over their entire habitat. In a great many cases, however, it limits the interested parties to a finite number, and usually a small one, making it possible for them to agree on a profitable strategy of utilization without thereby attracting challengers operating under the freedom of access to the high seas. Many fish stocks are, however, to a varying degree accessible outside the 200-mile jurisdiction, and this area is in principle open to anyone. This limits the efficacy of the 200-mile jurisdiction; the management of fish stocks that migrate far and wide would be much easier if national jurisdiction were extended to cover all of the world's oceans.

While national jurisdiction is a necessary condition for sustainability, it is not – as noted – sufficient in itself. So which institutional framework does supply the sufficient conditions? Clearly defined property rights over fish stocks would appear to be one such institution. A colleague of mine once asked the rhetorical question "why isn't the pig an endangered species?" Applying the same kind of ownership arrangement to fish as to pigs seems an eminently sensible way of ensuring the continued existence of fish stocks. Provided the rate of growth of the stocks is high enough to make them attractive as investment objects, the private owner would have a strong interest in preserving a sufficiently large stock to ensure future catches.

Yet we hardly see any such arrangements; the only marine animals to which private property rights arrangements are applied are oysters, and then only in certain places. There are several reasons for this. First, most fish stocks migrate far and wide, so enforcement of private property rights would be difficult. Second, migration of fish stocks between different jurisdictions makes it difficult to apply private property rights; it would entail a far-reaching cooperation among the states involved. Third, environmental concerns are increasingly being used as a justification for reducing catch levels.[6]

It bears noting that the rights to fish quota allocations that have developed over the last thirty years or so, often called individual transferable quotas (ITQs), do not amount to property rights to fish *stocks*. They are use rights, i.e., rights to catch a certain amount of fish over a certain period of time, usually a certain fraction of a total catch quota within a calendar year. While such rights are useful for encouraging an economically efficient utilization of a given fish quota and providing incentives to match fishing fleets to the long term catch prospects, in most cases they give the right holder no direct control over the resource base, i.e., the fish stock. Moreover, the total catch quota is usually determined by public authorities and not by the industry. ITQ regimes such as the one in Iceland are often wrongly accused of failing to rebuild depleted fish stocks, when the real culprits are politicians who sometimes give chosen segments of the industry a right to exceed their catch quotas. Furthermore, most governments which have put ITQs in place have been reluctant to make them private property in the fullest sense of the word; more often than not, the right to reallocate individual catch quotas and to do so without compensation has been explicitly asserted. This can only serve to blunt the incentives to conserve and to invest for the long term. That said, it is highly likely that ITQs have promoted fish stock conservation by giving individual fishing firms an asset whose value depends crucially on how well the fish stocks are managed. This, however, requires collective action; there is little the individual firm can do in isolation to promote conservation, and indeed it has an incentive to do the opposite by exceeding its quota, much as a member of a cartel has an incentive to produce over quota (see Hannesson (2004) for characteristics of and different experiences with ITQs).

7. Conclusion

Above it was shown that whether or not fish stocks should be exploited sustainably is a question of (1) their rate of growth compared to the rate of return on alternative investment, (2) the sensitivity of the unit cost of fish to the size of the fish stock, and (3) whether fish stocks have a value beyond their consumptive value. But even if we rule out the "mining" of fish stocks as an unlikely strategy, the application of the sustainability concept poses formidable operational problems. What would be the appropriate stock and catch level in a deterministic environment? There are many candidates for sustainability. And given that all fish stocks in the wild are subject to environmental fluctuations, how should the level of exploitation be modified to take account of these shifting fortunes? It is unlikely, although not entirely impossible, that sustainability in a variable environment would mean taking the same catch year after year or season after season. Furthermore, if the environment is so variable as to make some stocks virtually vanish for a prolonged period of time, how much weight should be put on the future? The more uncertain the future availability of the stock, the less that weight should be, and if the stock is virtually certain to disappear we would not care about sustainability at all.

I began this article by discussing changing technology and needs. These pose their own challenges to sustainable use of fish stocks. One of the collapse stories above (the Atlanto-Scandian herring) was attributed to a rapid technological change, the effects of which were not foreseen and were only belatedly understood. Technical change also contributed to the Northern cod debacle, through ever-more efficient trawlers and up-to-date fish-finding equipment. Such challenges will continue to be posed in the future. It will not always be possible to foresee the effects of technological change; it is likely that we will only learn about them through experience. This implies that mistakes will continue to be made as a necessary prerequisite for learning how to cope with the challenges of a new technology. The Peruvian anchovy story may not be so dissimilar; how could one know how to respond to the challenges of an El Niño event until it had played out? This makes it all the more essential that institutions be structured in such a way as to enable learning to take place.

Lastly there are the changing needs of humans. Since time immemorial, fish, whales and seals have been hunted for food and for materials such as fats and hides. Recently large, or at least vocal, parts of humanity have come to see some of those activities as immoral, especially seal and whale hunting. It has probably helped in that regard that the needs satisfied by seal and whale products can now be satisfied in many other ways, so that these activities are not critically important in any sense, except perhaps for some impoverished hunters in Greenland and Canada who used to get some income from selling seal skins. Sustainable exploitation of these animals has long since lost its meaning, although sustainability of stocks is occasionally advanced as a vicarious argument by some environmental advocacy groups who wish to ban the hunting of these animals altogether. Could the same happen to fisheries? The argument is increasingly being advanced that fish stocks must be managed so as to set aside sufficient forage for marine mammals. Such changes in "needs" of course have implications for how we choose between alternative but still sustainable fish management strategies.

Notes

1. The optimal trade-off is characterized by the equation (for a derivation, see Clark (1976)):

$$r = G'(S) - \frac{c'(S)G(S)}{p - c(S)}$$

where r is the discount rate, $G(S)$ is the surplus growth, $c(S)$ is the unit cost of fish, p is the price of fish, and apostrophe denotes derivative. If the unit cost of fish is constant and independent of the stock, the last term on the right hand side would vanish, and the optimum stock would be on the left side of the maximum of the surplus growth curve in Figure 1; or, in other words, we should take the sustainable yield from the smaller of the two stock levels supporting it. Since $p - c(S) > 0$ in any profitable fishery and $c'(S) \leq 0$ (a larger stock will, if anything, lower the unit cost of fish), the stock-dependent unit cost of fish pulls the optimal stock level to the right in Figure 1 and possibly to the right side of the maximum of the surplus growth curve.

   If the unit cost of fish is independent of the stock and the last term on the right vanishes, we could have a situation where sustainable use is not the optimal policy. If the marginal growth rate of the stock ($G'(S)$) is very low even for the smallest viable stock level (zero in Figure 1), we could have a situation where $G'(0) < r$. What this means is that the stock is so unproductive that it does not pay to invest in it. Any fish we do not take immediately can be regarded as an investment, yielding a return in the form of enhanced stock growth and lower future costs of fishing. This return must be compared with the rate of return on alternative investment.
2. The Monterey Aquarium, notorious for its environmental agenda, displays a diagram of the catches of the Peruvian anchovy as an example of how overfishing leads to collapses of fish stocks. The diagram ends in 1983, when catches had fallen to near-zero. As of July 2002 the Aquarium had not updated its depiction of this story, in spite of the fact that the fishery had recovered.
3. In recent years this herring stock has been mainly known as Norwegian spring spawning herring, as the fish spawn off the Norwegian coast. Before the collapse in the 1960s there were also spring spawning herring stocks near Iceland and the Faeroe Islands, and even near Greenland during the warm period of the 1920s and 30s (Vilhjálmsson 1997), but these stocks now appear to be extinct.
4. After 1977 fishing by foreign fishing fleets was greatly reduced, so their activities were hardly decisive, but certainly unhelpful. See Hannesson (1996, 90).
5. According to his memoirs (Cody 1904), p. viii.
6. For example, fish are either seen as animals worthy of preservation as such or as forage for other types of fish or marine mammals that certain groups seek to preserve. Absent government regulation, the fishing industry would be unlikely to take such considerations into account – unless it were compensated for the reduction in revenue.

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