

Sustainable Use of Populations and Overexploitation

Mikko Heino, *University of Bergen, Bergen, Norway*

Katja Enberg, *University of Bergen, Bergen, Norway*

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Sustainable use refers to exploiting a resource so that the resource is not depleted or permanently damaged. Sustainability is an internationally accepted minimal goal in managing biological resources. However, many populations are managed under more stringent goals, for example obtaining maximum sustainable biological or economic yield. Overexploitation refers to exploitation that is more intensive than such specific goals. While overexploitation is not sensible from societal point of view, in practice overexploitation often occurs because of the conflicting interests between individual exploiters and the public, and because individual exploiters often are maximizing short rather than long-term benefits. When sustainable exploitation is attempted, significant practical challenges remain in determining particular exploitation levels that would guarantee chosen management goals. Good intentions may be ruined if uncertainty is not properly accounted for, and overexploitation may also result from lack of precaution.

Introduction

Humans have exploited biological resources since the dawn of time, and still today, wild populations continue to be important sources of food, medicine, building material and other goods. However, exploitation represents an additional source of mortality to populations, and as a consequence, will result in abundance decline. However, unless exploitation is excessive, this decline is transient and a resource population will persist at some intermediate abundance, below the pristine level. Sustainable exploitation is possible because when population abundance is decreased, natural regulatory mechanisms partially relax, compensating for additional mortality from exploitation. However, if this natural capacity to compensate for additional mortality is exceeded, population will continue to decline and will eventually crash. **See also:** [Conservation of Populations and Species](#)

The goal that biological resources should be utilized sustainably is solidly established in international agreements

and declarations. Already in the declaration of the United Nations conference on Human Environment from 1972 it was stated that 'The natural resources of the earth, including the air, water, land, flora and fauna and especially representative samples of natural ecosystems, must be safeguarded for the benefit of present and future generations through careful planning or management, as appropriate.' The declaration of the United Nations conference on Environment and Development at Rio de Janeiro in June 1992 included two important principles related to the sustainable use of our natural resources. Principle 7 calls for ecosystem approach to resource management by stating that 'States shall cooperate in a spirit of global partnership to conserve, protect and restore the health and integrity of the Earth's ecosystem', and principle 15 requests the adoption of the precautionary approach: 'In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation'. Recently, the Implementation Plan of the World Summit on Sustainable Development ('Johannesburg Summit') from 2002 promotes sustainable use of biological diversity in general and sustainable fisheries, forestry and agriculture in particular.

Despite good intentions, sustainability is not necessarily the norm. Instead, there are numerous examples of exploitation of populations that is intensive enough to threaten future use. This can loosely be defined as overexploitation.

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Why overexploitation easily occurs whenever humans have capacity for doing so can often be understood as resulting from the conflicting interests between individual exploiters and the public, and between maximizing short and long-term benefits.

Concepts and Definitions

Traditional approaches to defining sustainability and overexploitation

Sustainable use refers to harvesting or using a resource so that the resource is not depleted or permanently damaged, and the benefits of the use can in principle be maintained indefinitely. However, what this exactly means is not always clear. The weakest requirement for sustainability is that exploitation is not threatening the resource population with biological extinction – as long as population is not fully depleted, some harvesting will be possible, and some benefits can thus be maintained.

A more conservative requirement for sustainability is avoiding economic extinction: the sparser the resource is exploitation becomes more difficult and thereby more costly, exploitation often becomes unprofitable well before biological extinction. However, this is not always the case. Some targets are easy to spot even when rare, e.g. big animals such as elephants, and those that aggregate to some hot spots known to exploiters. Moreover, market demand for some resources may remain high even when their supply diminishes. If consumers are willing to pay more, declining supply of a resource then leads to a price increase that may offset increased exploitation costs. This typically happens for products that enter the luxury food markets or that have (purported) medical properties. For example, some fish species such as southern bluefin tuna become more and more valuable the scarcer they get. This means that the economic return from a given effort also depends on the desirability of the harvested species.

In practice, however, the requirements for sustainability are often more stringent than just avoiding biological or economic extinction: there is an expectation that the potential benefits are maintained at some 'fair' level, that is, actual benefits are reasonably high relative to the best possible benefits. Where the limit between sustainable and unsustainable exploitation should be drawn is not a scientific question as such, but must reflect the objectives set by the society. This, in turn, is tightly linked to valuation of different use and nonuse values of populations and ecosystems (e.g. Costanza *et al.*, 1997).

Overexploitation refers to exploitation that is more intensive than some agreed limit. Again, it is not in the realm of science to define such limit, although scientists can advise on possible choices. Overexploitation can be defined as unsustainable, or vice versa, but often these terms are not tightly coupled.

Terms sustainable exploitation and overexploitation can be illustrated with an example. The simplest model

describing dynamics of an exploited population is an extension of the logistic population growth model, $dN/dt = r(1 - N/K)N$, where the rate of change in population abundance depends on population abundance itself and on the intrinsic rate of population increase r , and a density-dependent effect, strength of which is determined by population size relative to the carrying capacity K . This model can be amended with a negative term describing exploitation. The exploitation rate is the product of exploitation effort E , population abundance (same effort gives more yield from a dense population than from a sparse one!) and parameter q that relates effort to yield at a given population abundance (efficient exploiters catch more for the same nominal effort). The full model is now $dN/dt = r(1 - N/K)N - qEN$. The behaviour of this model is well-known and is illustrated in **Figure 1**. Without effort there can be no yield, whereas with too high effort (the exact limit is determined by the ratio r/q) the population declines to extinction. In between these extremes, the equilibrium yield has a parabola-shaped dependence on effort. The maximum yield that can be sustained indefinitely is obtained at an intermediate level of effort, and is termed 'maximum sustainable yield' (MSY). **See also:** [Fisheries Management](#); [Population Dynamics: Introduction](#)

Within the realm of this model, obtaining MSY is one concrete management objective. This is achieved by exploiting at an intermediate effort, E_{MSY} . With respect to this management objective, exploiting at higher effort represents overexploitation. Higher effort will initially provide higher yield, but yield will eventually be diminished because the standing stock that produces the yield declines below the optimal level. This is the traditional definition of biological overexploitation.

Other management objectives are entirely possible, and result in other definitions of overexploitation. For example, managers could pursue maximum economic yield, which is typically achieved with a lower effort than MSY because costs increase with effort, and yield per unit effort is higher the lower is the effort. When effort is higher than the one providing maximum economic yield, but lower than the one providing MSY, the population could be classified as economically overexploited, but biologically 'underexploited'.

'Sustainability' is also in the eye of the beholder. One choice is to link sustainable use to the absence of overexploitation. However, if there is modest biological overexploitation (effort is somewhat higher than E_{MSY}), the resource population cannot be considered depleted or damaged, and that effort could be upheld indefinitely. In general, it is important to appreciate that overexploitation does not imply population being driven close to extinction. Nevertheless, biological overexploitation is unsustainable in the strict sense since the benefits to future generations are compromised: future yields could be increased, but only when allowing for lower yields during the period when the resource is recovering.

Another important point illustrated by the logistic model is that exploitation always reduces equilibrium

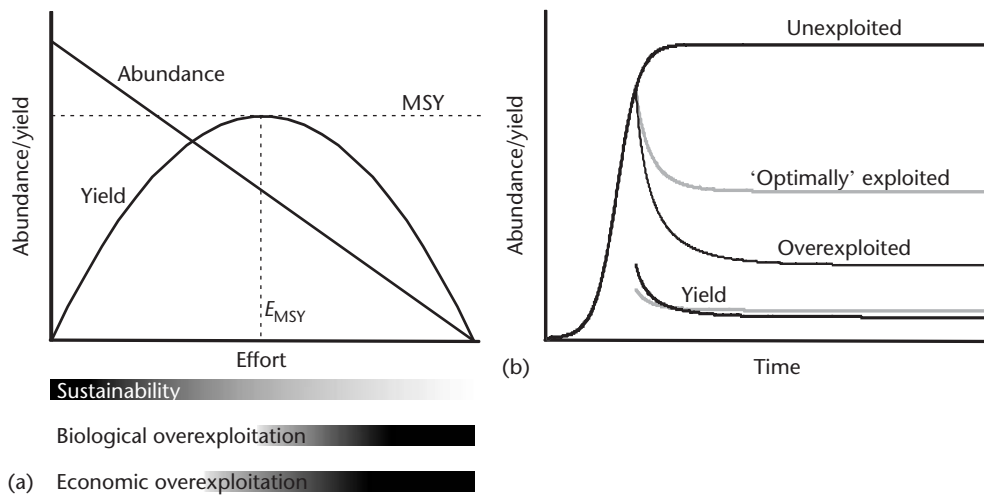


Figure 1 (a) The relationships between exploitation effort, equilibrium population abundance and equilibrium yield in the logistic single-species model. For too high effort, population goes extinct. The dependence between effort and yield is dome-shaped, with the maximum sustainable yield (MSY) obtained in the middle. Sustainability declines with effort, but threshold beyond which exploitation is 'unsustainable' is a matter of debate. Similarly, the threshold for 'overexploitation' is a matter of debate. In this example, it is assumed that obtaining MSY is the management objective, and that effort levels that are higher than one giving MSY are considered biological overexploitation. Economic yield is usually maximized at a lower effort than biological yield. Consequently, economic overexploitation may be scored even when biological overexploitation is not yet occurring. While the detailed relationships depicted here depend on the model, the overall picture is model-independent. (b) Dynamics of unexploited and exploited population in the logistic model. Unexploited population reaches carrying capacity (thick black curve). If exploitation is started, abundance declines. In the logistic model, intermediate effort (thick grey curve) gives the highest sustainable yield, but this also results in substantial reduction in equilibrium abundance. Notice that overexploitation (thin black curve) gives higher initial yield than exploiting with effort giving MSY.

abundance of the resource, and that MSY occurs at population abundance of one half of the carrying capacity (Figure 1). Naturally, the latter prediction holds for the logistic model, and other models may give different predictions. Nevertheless, it remains a fact that extracting a high yield from a single population requires reducing population abundance well below pristine levels. Similarly, if exploitation starts from zero, initial exploitation rates can be very high without compromising future yields (and thus sustainable), even if such high rate would be unsustainable in the long run.

Modern extensions

The classic view on sustainability and overexploitation outlined above focuses on single populations managed for high biological and/or economic yield. However, nowadays this perspective is often deemed insufficient. Partly this is caused by the apparent failures of single species approaches in achieving sustainability. Maybe even more importantly, increased understanding of ecosystem functioning has guided us towards more holistic view of resource management, with greater appreciation of nonuse ecosystem services.

Single species models suggest that MSY is obtained when the resource is considerably reduced relative to its preexploitation abundance; in the logistic model, this happens at half of preexploitation abundance. However, no species exist in isolation, and the reduced abundance of the target species may have significant influence on other species that interact with it as predators, competitors or prey. Resource species may also be a critical habitat element for

other species (e.g. for parasites and epiphytes). If such effects are taken into account, exploitation may have to be considered unsustainable long before that would be the case under the single species paradigm. Moreover, it is well known that when exploiting interacting populations, the combined MSY is not the sum of the single population MSYs (Walters *et al.*, 2005). Therefore, whether a population is considered overexploited may depend on the exploitation status of interacting species.

Exploitation may also have indirect effects on the exploited species. For example, bottom trawling may severely disturb the sea floor, decimating hard-bodied animals such as corals and sponges. In addition to this being a biodiversity concern on its own right, these animals may provide habitat to commercial species, particularly juveniles. Destructive exploitation practices thus challenge sustainability from the narrow, resource population perspective, as well as from ecosystem and biodiversity perspectives.

We have also come to realize completely new kinds of threats that exploitation pose to sustainability. Increased mortality caused by harvesting changes not only the size, structure and dynamics of target populations, but may also cause long-lasting alterations in life history or behavioural traits (Jørgensen *et al.*, 2007). What really matters in the course of evolution is passing on genes to the next generation, and only individuals that survive to reproduce can achieve this. Consequently, survival is hard currency in evolution. Heritable variability exists in behavioural and life history traits that influence how individuals are able to survive and reproduce when mortality risks change. The changes in the mortality schedule caused by exploitation

are therefore prone to cause changes also in the heritable traits. For example, many fishing gears are size selective, often with a certain minimum size. In many fish species, large individuals are most successful breeders, and, most importantly, delaying maturation to a later age and size is often a beneficial strategy. However, when fishing gear selects from a certain minimum size upwards, fish that have not reached maturation before entering the size range vulnerable to harvesting may never get a chance to reproduce. Consequently, the individuals that mature at smaller size will be the ones that carry on their genes to the next generation. The same has occurred in hunted populations: hunters may value for example big antlers, which leads to diminished occurrence of such antlers in the population, as the individuals/males with another kind of headset will get more offspring by just surviving longer. In addition to such declines in quality of harvest, theory also predicts that quantity of harvest will decline. Exploitation-induced evolution thus challenges sustainability of current exploitation practices, even when they are ecologically sustainable. Furthermore, it is important to realize that such evolutionary changes in harvested species may be slow, or in some cases even impossible, to reverse.

Challenges

Sustainable use of biological resources is in the best interest of the humankind, but it is not necessarily in the best interest of individual exploiters. Any resource that is exploitable by more than one party is vulnerable to phenomenon commonly referred to as the 'tragedy of the commons'. This term, brought to common knowledge by ecologist Garrett Hardin in 1968, refers to situations where resources available for everyone tend to be exploited heavier and heavier over time, such that they eventually become overexploited and may even be ruined. This follows from rational individual behaviour because of the asymmetry in sharing the benefits and costs of increased individual exploitation rate: the exploiting agent will receive all the benefits of increased exploitation rate, whereas the costs are shared by all exploiting agents together (the utilized resource is no longer available to others, and everybody suffers from the consequences of overexploitation). **See also:** [Fisheries Management](#)

The situation is further accentuated by the fact that increased exploitation will almost always bring short-term benefits, even when the resource is overexploited and increased exploitation reduces benefits in medium and long term. When there is a risk that future benefits cannot be fully realized, or capital obtained by cashing the whole resource stock can be invested more profitably than the resource renews itself, conserving a resource for the future becomes less attractive. Risk and profitability of alternative investments is reflected as discounting; high discount rates are a challenge for sustainability as future benefits are rapidly devalued. However, appropriate discount rates to

be used in management of renewable resources are a matter of debate (Carpenter *et al.*, 2007).

There are three types of solutions that may help to avoid the tragedy of the commons. First, exploiting agents may choose to cooperate, acknowledging that on the long term they are better off if they do not try to maximize their short-term benefits. This is most likely to succeed if there are just a few exploiting agents, such that they can more easily monitor each other and cheating is avoided. Second, an authority (typically representing the state) may assume control over the resource, and impose regulations that prevent excessive exploitation. For example, exploitation might require a permit, and be subject to a quota. However, permit holders could still increase their individual exploitation rates, and be attracted to exceed the quota. Third, the resource could be privatized. Owner of a resource will have incentive to harvest it sustainably in order to maintain the value of the asset. This assumes that the resource could be controlled, and that cashing the resource stock is not an attractive option.

Challenges will remain even if there is a will for sustainable exploitation and a governance system that facilitates sustainability. Determining sustainable exploitation level requires considerable knowledge on the exploited population. This knowledge is typically obtained by studying how exploitation in the past has influenced the abundance and dynamics of the exploited population. A seemingly attractive option is to study the empirical relationship between effort and yield. In principle, such data allow deriving the curve relating effort and equilibrium yield (Figure 1 gives an example how this curve could look like). In practice, such relationships tend to be very noisy, and consequently, estimates of effort levels that would allow for near-maximal yield or that would lead to stock collapse can only be known with large uncertainty. Moreover, a robust estimate of MSY (or other benchmarks that could be used as management targets) is usually not possible without letting effort and mortality to exceed the MSY level, that is, without overexploiting the population. At this stage, it is probably difficult to curb exploitation to levels that would be more sustainable.

With more extensive monitoring and data collection, it is possible to reduce uncertainty about the consequences of exploitation and about how management targets are reached. Estimation uncertainty can also be reduced by making specific biological assumptions about the exploited species, but these assumptions are difficult to validate, and consequently, model uncertainty may increase. In any case, uncertainty will always remain, and managers of populations have to cope with that. The precautionary principle suggests that in face of uncertainty, it is best to err on the safe side. This means that the more there is uncertainty, the more conservative exploitation levels should be used. However, while the international agreements prompt for such risk aversion in natural resource management, managers may in reality use uncertainty as an argument against cautious approaches and opt for taking considerable risks.

Sustainability in Practice

History

While technological innovations and increasing human population have made sustainable resource use increasingly difficult, there are numerous examples of human exploitation leading to severe population decrease and even extinction starting already from the times when humans were spreading across the face of the earth. It is intriguing that the radiation of human species, which started from Africa some 7 million years ago, resulted in extinctions of numerous species in the different continents that almost perfectly coincide with the arrival of humans (Diamond, 1997). Many of these species were large mammals or birds that were most likely hunted to extinction. There are also famous examples of extinctions on more recent history caused by human overexploitation. Dodo, a flightless, 1 m tall and 20 kg heavy bird of Mauritius, went extinct in mid-to-late seventeenth century, partly as a result of hunting but also partly because other human activity such as habitat destruction and introduced species. Pacific islands abound with examples of extinctions likely caused by overexploitation. In New Zealand, many species of moa were roaming, the largest of which, giant moa, was 3 m tall and weighted 250 kg. All moa species became extinct mainly due to hunting by around AD 1500, within some hundred years (according to some estimates, only within one century) after the arrival of maori people.

In marine environment, a classical example of catastrophic overexploitation is the Steller's sea cow, a species that was discovered in 1741, but declared extinct only few decades later in 1768. Still, the idea that oceanic fisheries were inexhaustible because of vastness of the ocean prevailed until modern times, as immortalized by the famous citation from 1883 by T. H. Huxley, well-known proponent of Darwinism and then fisheries inspector. However, in the islands of the Pacific Ocean, the villagers had found out thousands of years before that at least coastal and reef fisheries do indeed collapse as a result of overfishing. Probably for this reason the traditional management on these islands developed towards limited access, with often kinship-based groups of individuals having rights to a certain fishing area (Jennings *et al.*, 2001). This kind of development was necessary because of the strongly limited resources on such isolated islands.

Present status

Because of the proven ability of humans to exterminate species from the face of the Earth, a number of agreements and treaties have been made in order to achieve sustainability in the use of natural resources. In marine environment, the United Nations Convention on Law of the Sea (UNCLOS) from 1982 defines rights as well as the responsibilities of coastal states, including an unambiguous responsibility of sustainable exploitation: the convention dictates that states must 'maintain or restore populations

of harvested species at levels which can produce the maximum sustainable yield'. However, the convention does not provide means for achieving sustainability, and moreover, it does not cover international waters. The Convention on Biological Diversity from 1992 is a more all-encompassing part of international law, obliging parties to sustainably use components of biological diversity. With regards to the trade of wild animals and plants, the International Union for Conservation of Nature and Natural Resources (IUCN) together with World Wide Fund for Nature (WWF) founded in 1976 a joint international organization TRAFFIC. In close cooperation with the Secretariat of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), TRAFFIC works globally for ensuring that the wildlife trade is not posing a threat to nature conservation.

An important component of sustainable use is monitoring the status of the exploited populations. The IUCN Red List of Threatened Species, created first in 1963, lists very comprehensively and objectively the conservation status of more than 40 000 (at the time of writing) species in terrestrial, marine and freshwater environments. The Red List categorizes species according to their extinction risk, and also incorporates the major threats to any listed species. Species extinct due to or threatened mainly by harvesting are shown in **Figure 2**. These statistics suggest that most threatened species are found in terrestrial environments; this may be due to better and easier surveying of terrestrial areas compared to particularly marine environments. **See also: Biodiversity – Threats**

The most comprehensible international statistics on exploitation and sustainability exist on fisheries. The Food and Agriculture Organization (FAO) of the United Nations keeps statistics of exploited fish populations, and classifies them into different categories based on the exploitation status. From these statistics (**Figure 3**) it is easy to see that the proportion of fish populations exploited to full extend or more (i.e. overexploited) has increased during the

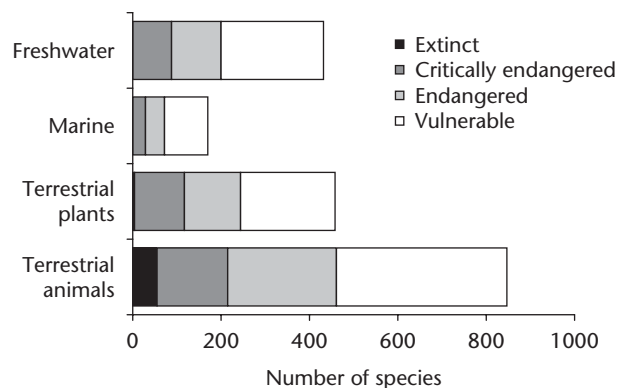


Figure 2 Number of species extinct or threatened by harvesting according to IUCN Red List. This includes hunting and gathering for food, medicine, fuel, material and cultural, scientific and leisure activities. No marine or freshwater plant species were listed. Data from the International Union for Conservation of Nature and Natural Resources (IUCN; <http://www.iucnredlist.org/>, accessed in March 2008).

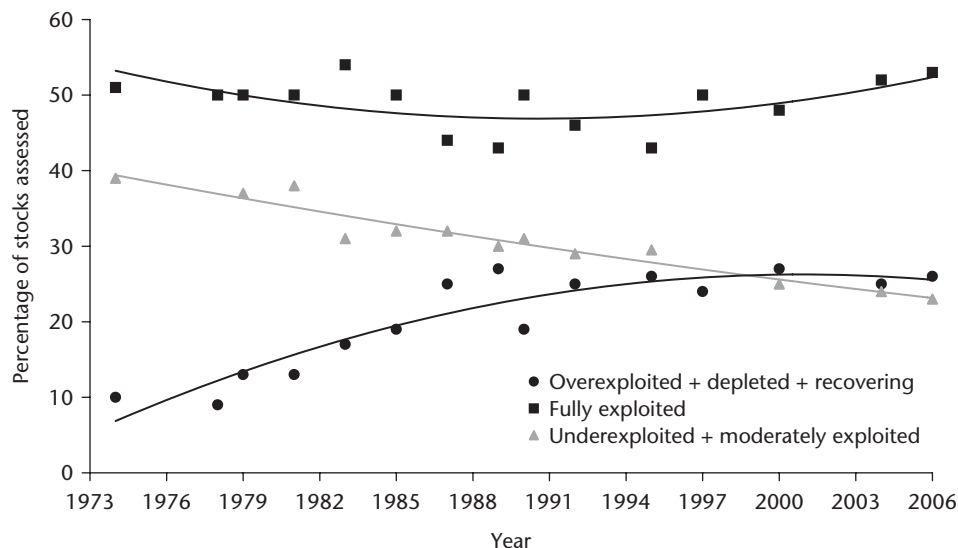


Figure 3 State of the world marine fish stocks (FAO, 2007). FAO started monitoring the world's fish stocks in 1974, and categorizes them in different groups based on the level they have been exploited (see figure legend). The percentage of stocks 'underexploited' or 'moderately harvested' has decreased while the percentage of stocks 'fully' or 'overexploited' has increased. Underexploited and moderately exploited stocks could produce higher sustainable yields if exploited more, whereas fully exploited stocks are producing catches that are at or close to their maximum sustainable limits. Overexploited, depleted and recovering stocks are yielding less than their maximum potential owing to excess fishing pressure, with no possibilities in the short or medium term of further expansion. Reproduced from *The State of World Fisheries and Aquaculture (2006)*, with permission from the Food and Agriculture Organization of the United Nations.

last decades, although it seems to have stabilized in the most recent years. Fortunately, there are also examples of successful management, and moreover, proof that humans have been able to learn from earlier management failures. For example, Norwegian spring spawning herring stock collapsed in the end of 1960s largely due to overharvesting. A moratorium was established to let the population recover, and after more than a decade the stock finally started recovering. Currently, the stock is again among the most valuable fish stocks worldwide, and is harvested under a conservative and precautionary management plan.

Whaling has been carried out at least for 8000 years, and has, in more recent times, resulted in 5 out of the 13 species of great whales becoming endangered. International Whaling Commission (IWC) was founded in 1946, originally to take care of the whale stocks for sustainable whaling and recognizing that overexploitation was threatening many whale populations. The role of IWC has, however, changed during the years: from an organization of 15 whaling nations, it has developed into an organization including 77 nations (many of which are landlocked) that essentially promotes protection of whales. IWC is nowadays torn between pro- and antiwhaling nations, the former arguing that the population sizes of certain whale species allow sustainable whaling, while the latter oppose this view from scientific, practical or moral grounds.

The Way Forward?

The road to successful sustainable management might seem bumpy, but there are some features that help in

achieving sustainability, at least in fisheries: geographical isolation, fleet capacity control, right ownership and stakeholder involvement (Dankel *et al.*, 2008). Geographical isolation helps in limiting the number of exploiters, whereas fleet capacity control simply helps avoiding one of the most common problems with contemporary fisheries, overcapacity. Ownership rights and stakeholder involvement both work by giving the exploiters or people involved in using the resource more responsibility over the sustainability. For example, the game population estimates in Finland are done together with the hunters themselves. The most important means for monitoring the Finnish moose population has already for three decades been the observations produced by the hunters – and the moose population management has been rather successful. **See also: Fisheries Management**

A necessary condition for sustainable exploitation is that the exploiters are in position to do so. But in the developing world, exploitation of wild populations is the lifeline of many people and communities. Even though sustainability is in the interests of these people, their daily needs must come first, and they may be unable to adopt more sustainable practices without outside assistance. This is also well recognized in the United Nations driven international process to promote sustainability: ecological sustainability is a necessary condition for social and economic sustainability, but ecological sustainability cannot be achieved without parallel poverty reduction.

In general, there are two complementary governance approaches to promote sustainability. One is to use rules and laws to regulate exploitation activities such that sustainability is achieved. Naturally this requires sufficient

knowledge about resource populations. However, often regulations are such that they do not provide exploiters incentives to conserve the resources. Under these conditions, it is essential that exploitation is under sufficient monitoring, and the regulations are enforced.

The second approach is to change the conditions under which exploiters operate such that it is in the best interest of exploiters themselves to act sustainably. In other words, governance should provide exploiters incentives for sustainable exploitation. This can be achieved by giving the exploiters some kind of ownership to the resources, because it is in the interests of owners of the resources to avoid excessive exploitation such that the long-term value of their property is maintained. Here it is important that ownership is given to the whole harvested population, such that the owners receive all benefits, and carry all the costs, of their own actions. But the groups having the ownership must not be too large, as in large groups cooperation and social control may break down and individual exploiters may have divergent interests, making cheating more likely. It is also not to be taken granted that ownership guarantees subtler aspects of sustainability, such as ecosystem dimensions whose effects unfold at longer time scales.

In reality, both carrot and stick are probably needed. Entirely rule-based systems are prone to cheating, and enforcement may become costly and difficult. Incentive-based systems are not suited for spatially extended resources because too large or too heterogeneous owner groups may fail to cooperate. At the same time, the role of education must not be neglected. While exploiters often have a fair understanding of dynamics of core resources in short term, there are less obvious ecological and evolutionary effects that may compromise sustainability in medium and long term.

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