Fisheries Management

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Based in part on the previous version of this eLS article 'Fisheries Management' (2007) by Daniel Pauly.

Advanced article

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Online posting date: 15th September 2014

Fisheries management is the set of science-based procedures used by government institutions to regulate fishers' access to fisheries resources; this involves temporal and spatial restrictions on the deployment of fishing gear, restrictions on features of these gear and constraints on the species and size composition of the catch, and its overall magnitude. The traditional goal of fisheries management was to achieve maximum sustainable yields. Maximum economic yields are obtained with slightly lower catches from larger fish stocks. Modern fisheries management aims for minimising the impact of fishing on the ecosystem and considers trophic interactions when determining catch levels. A new challenge is the assessment and management of data-limited fish stocks, which constitute about three-fourth of the exploited stocks.

Introduction

Humans have been catching fish since time immemorial. Indeed, the first archaeological evidence for fishing – elaborately carved harpoons – have been found at sites dated to 80 000 years ago in the Congo Basin, not long after the emergence of *Homo sapiens*. Characteristically, these finds were associated with the remains of a now extinct species of giant catfish. **See also**: Human Evolution: Radiations in the Last 300 000 Years; Natural Selection: Responses to Current (Anthropogenic) Environmental Changes

Our tools have much evolved since, but the tendency to overexploit local fish populations, then to move on to the next available resource, is well entrenched (Ludwig *et al.*, 1993). Most of our interactions with fish now occur in the form of fisheries, the organised catching of fishes and aquatic invertebrates (henceforth 'fish'); fisheries management regulates the activities and industries based thereon. **See also**: Urban Ecology: Patterns of Population Growth and Ecological Effects

Fisheries management, in principle, aims at adjusting the level of extraction such that relatively high catches can be sustained year after year – hence the concept of 'maximum sustainable yield' (MSY).

With regards to any given fishery, this task of fisheries management can be readily decomposed into two equally challenging subtasks: (1) estimating MSY and/or the corresponding level of fishing effort (f_{MSY}) and (2) ensuring that the level of fishing effort does not exceed f_{MSY}.

Item (1) typically defines the 'stock assessments' performed by fisheries biologists employed by government agencies (typically part of the ministry of agriculture and food), in collaboration (or competition) with university-based biologists, and usually pertaining to single-species fisheries.

Item (2), however, is typically the task of senior civil servants and politicians interacting with the private sector (i.e. industry representatives), but increasingly also with other stakeholders, notably environmental groups. The two sets of activities implied here are described briefly below.

Traditional Stock Assessment

Fisheries science has a long tradition of reducing the environmental context of fish stocks into three numbers: the rate of natural mortality (M), the rate of somatic growth (K) and the number of recruits (R) (eqns (1), (2), (3)). In other words, the predation by other species, the prevalence of diseases and the harshness of the environment are summarised in their impact on the survival of adults; the availability of food, its nutritional value and the effort associated with its hunt and assimilation are summarised in the speed by which individual fish reach their maximum size; and the inter-annual variability in

eLS subject area: Ecology

How to cite:
Pauly, Daniel; and Froese, Rainer (September 2014) Fisheries Management. In: eLS. John Wiley & Sons, Ltd: Chichester.
DOI: 10.1002/9780470015902.a0003252.pub3

environmental conditions that determine the survival of eggs and larvae are summarised in the number of individuals surviving to the stage of recruits that join the exploited population. **See also**: Deep-Ocean Ecosystems; Population Dynamics: Introduction; Shallow Seas Ecosystems

This approach for reducing complexity has served the discipline rather well, notably by enabling the emergence of the conceptual apparatus and the mathematical models through which 'overfishing' can be defined and diagnosed. **See also**: Environmental Impact Assessment; Natural Selection: Responses to Current (Anthropogenic) Environmental Changes

These models are of two basic types, each with innumerable variants:

1. Analytic models, wherein the processes referred to are explicitly taken into account (**Figure 1**).
2. Surplus production models, wherein these processes are only implicit.

An important representative of the models in (1) is the yield-per-recruit (Y/R) model of Beverton and Holt (1957), which incorporates an explicit equation for the growth of fish, of the form shown in eqn (1), where W_t is the mean weight of the fish at age t; W_∞ is the mean weight the fish would reach if they were to grow forever; K is the rate (of dimension time^{-1}) at which W_∞ is approached; t_0 sets the origin of the growth curve and b is the exponent of a length/weight relationship of the form $W = aL^b$.

$$W_t = W_\infty \left(1 - e^{-K(t-t_0)}\right)^b \qquad (1)$$

The Y/R model also assumes mortality to follow a negative exponential curve of the form shown in eqn (2), where N_{t2} is the number of survivors from time t_1 to t_2, given a rate of total mortality Z, itself the sum of $M + F$ (see **Figure 1**).

$$N_{t2} = N_{t1} e^{-Z(t_2 - t_1)} \qquad (2)$$

From these, Y/R (i.e. the catch that can be expected per young fish entering the fishery) can be obtained from eqn (3), where $r_1 = t_c - t_0$ is the mean age at first capture by the gear used in a given fishery; t_r is the mean age at which young fish 'recruit to', that is, enter the fishing grounds and all remaining parameters are as defined above.

$$Y/R = FW_\infty e^{-M(t_c - t_r)} \left(\frac{1}{Z} - \frac{3e^{-Kr_1}}{Z+K} + \frac{3e^{-2Kr_1}}{Z+2K} - \frac{e^{-3Kr_1}}{Z+3K} \right) \qquad (3)$$

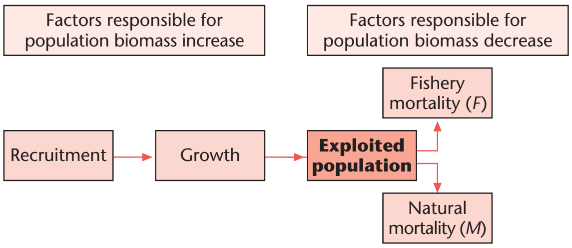

Figure 1 The four factors thought to matter in classical fish population dynamics. Note that, in this framework, the sole link of a given population to the other populations of fish, and to the ecosystem in general, is its natural mortality (M). Food consumption, required for growth (as per eqn (1)) and reproduction, required for recruitment, are usually not considered explicitly. Adapted from Russel (1931).

This forbidding-looking equation is presented here for two reasons:

1. It neatly illustrates that reasonable inferences can be derived on the status of a fishery and on possible remedial action (see **Figure 2**), even in the absence of detailed knowledge on environmental variability.
2. It illustrates the tendency, manifested early in the development of fisheries science, to rely on computation-intensive approaches to reach conclusions that are often counterintuitive, a trend that earlier helped it advance very fast, but which may contribute to a growing alienation between fisheries science and its client community.

One such counterintuitive result is the prediction of eqn (3) and **Figure 2** that killing fewer fish at a later age or size will optimise yields. This stems from the fact that fish grow throughout their lives and reach their maximum growth rate only at approximately two-third of their maximum length, while typical size at first capture is approximately one-fourth of maximum length, well before maturity is reached (Froese *et al.*, 2008).

Equation (3) and its many variants have provided the key reason for fisheries scientists, in the last decades, to sample exploited fish populations and to estimate the growth and mortality of the fishes therein.

In polar, temperate and subtropical waters, estimation of growth and mortality tends to rely on the annual structures, similar to the rings of trees, that are formed annually on the otoliths ('earbones'), scales and other hard parts of fin fishes (Jearld, 1983). In the tropics, where seasonal variations of water temperature and other environmental parameters tend to be slight, fisheries scientists usually rely on seasonal changes in the composition of sample length–frequency distributions to draw inferences on growth and mortality (Pauly, 1998). Length-based methods are also commonly used for invertebrates such as shrimps, which do not form age-related structures on their hard parts.

However, approaches for estimating ages based on daily structures in the otoliths of fin fishes, and similar organs in invertebrates such as squids, though sometimes used for validation of length-based results, are not used for routine estimation of growth and mortality, owing to their tediousness and cost. The latter is also a limitation for approaches relying on mark-recapture studies.

In contrast to analytical models, surplus production models do not differentiate between the factor contributing to stock (= population) increase, and those leading to

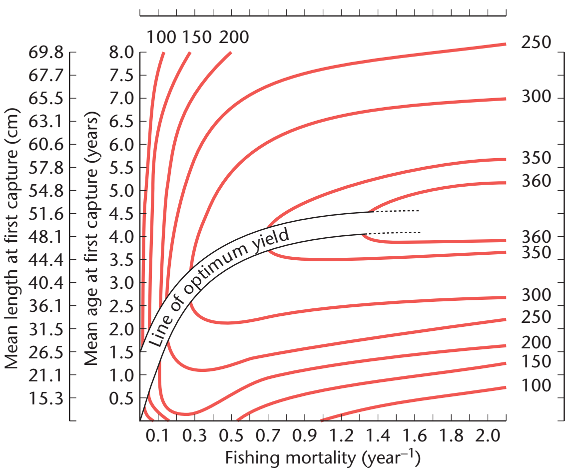

Figure 2 Yield-per-recruit isopleth diagram for a southeast Asian red snapper, generated using eqn (3) for different values of fishing mortality (F) and mean age at first capture (t_c), implying different body size and hence mesh sizes. Most fisheries tend to use meshes that are too small, and fishing mortalities that are too high, for the fish to be able to realise their growth potential (here approximately 300 g per recruit). Hence Y/R analysis often leads to the result, counterintuitive at first glance, that yield (Y) can be increased, whatever the number of recruits (R), by reducing fishing effort and increasing mesh sizes.

decrease (in **Figure 1**). Rather, recruitment, individual growth and natural mortality are jointly assumed to lead to a certain rate of net population growth (say 20% per year), applied to the biomass (or size) of the population, but declining near carrying capacity. Thus, for both a large population near carrying capacity and a depleted population far below carrying capacity, growth in weight can be assumed to be small. Conversely, population growth is assumed to be high when the biomass of the population is in between these two extremes. **See also**: Population Structure

In the most commonly used form of the model (**Figure 3a**), population growth is highest when the biomass is reduced to half the level at carrying capacity (B_0). Thus, if fishing effort is such that it maintains stock biomass at $B_0/2$, the corresponding catch rate (e.g. in tonnes per year) will consist of the maximum sustainable surplus production (rate) of the stock. Hence it can be argued that 'sustainability', embodied in the concept of MSY(**Figure 3**), became part of fisheries research as early as the mid-1950s, when surplus production models became operational (Schaefer, 1954).

Yet, in spite of the basic soundness of both analytic and surplus production models, and the logic behind them, there are very few fisheries in the world whose mesh size and effort levels correspond to what fisheries scientists consider optimal. Indeed, fisheries catches, worldwide, are not as high as they could be, and population biomasses are much lower than they would be, were the resources optimally managed. Universally, this is due to overcapacity of the fishing fleets, not to effort being too low.

This state of affairs has a number of causes, the most important of which is the legal status of fish populations; the implications of these are discussed next.

Open-access Resources: Economic Implications

Under most jurisdictions, fish belong to no one (or to all, which is the same in practice) until they are in the possession of the fisher(s) who caught them. Combined with the fact that, in most countries, anyone can decide to become a fisher and/or invest in fishing; this leads, through the mechanisms highlighted in **Figure 3**, to most of the world's fisheries suffering from biological overfishing (defined here as having effort levels in excess of f_{MSY}, usually also associated with growth overfishing as defined by a Y/R analysis; **Figure 2**). But also in countries with restricted access to highly regulated fisheries, previous over-investments in developing fisheries resulted in the same dynamics and economic consequences as shown in **Figure 3**. Interestingly, the effect of low-cost labour alluded to in **Figure 3d** also applies to part-time fishers in developed countries, who earn their main income in another job and thus can continue fishing of depleted stocks even if costs exceed the value of the catch.

Classical approaches for 'input' control (seasonal area closures, limited number of days at sea, various gear restrictions, etc.) have largely failed to stem the tide, and overcapacity (excessively large fleet, relative to potential catches) has become a global scourge (Pauly *et al*., 2002).

Although there is a widespread consensus among fisheries scientists and managers as to the seriousness of this state of affairs, efforts to overcome it have been largely stymied, in most countries, by special pleading by the various components of the fisheries sector (Froese, 2011). Indeed, the consequences of overfishing – falling income for labour and stagnating profits for firms – are aggravated by the various subsidies handed over by short-sighted politicians in response to such pleading, as illustrated schematically in **Figure 3b**. As a result, most fisheries fail to generate net benefits for the societies that sustain them (Christy, 1997).

Signs of hope are, however, visible in some countries (notably in New Zealand, Australia, the United States and most recently Europe) which have reformed their fisheries management to phase out overfishing and to rebuild fish stocks above levels that are capable of producing MSY.

Rights-based Fisheries

The assumption that open access is the root cause of overfishing has led fisheries economists to the concept of individual transferable quotas (ITQ), wherein the right to catch a fixed fraction of the total allowable catch (TAC, determined with analytic and/or surplus production models) is treated as a commodity that can be held in perpetuity or sold/bought at will. While the initial allocation of ITQs always causes problems of equity, rights-based fisheries, now well established in some parts of the world (notably in Alaska, Australia, Iceland and New

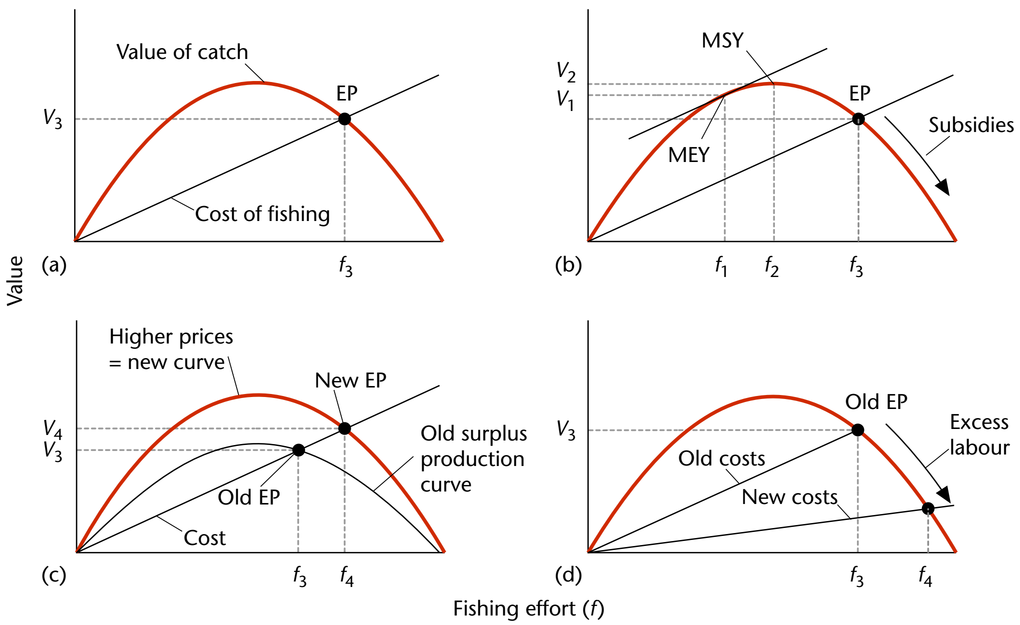

Figure 3 Schematic representation of the key economic factors affecting fisheries. (a) Basic model, in which fishing costs are assumed to be proportional to fishing effort (f), and gross returns proportional to catches (parabola). (b) During the typical development of a new fishery, f will increase past maximum economic yield (MEY) at f_1 (where the economic rent, i.e. the difference between total costs and gross returns, is highest), and past MSY (at f_2), until the equilibrium point (EP, at f_3), where costs and returns are equal, that is, where the economic rent is completely dissipated. In this situation, subsidies, by reducing costs, increase the level of effort at which EP occurs, and thus decrease catches. (c) Price increases, by increasing gross returns, increase the level of effort at which the rent will be dissipated (i.e. from f_3 to f_4), and hence foster overfishing, just as subsidies do. (d) In open access small-scale fisheries, labour is a major cost factor; when its value tends towards zero (as occurs when there is a large excess of rural labour or if fishing is a part-time job), resources may become severely depleted.

Zealand), have indeed displayed an ability to shed excess fishing capacity. However, the track record of ITQ-based management in preventing or reducing overfishing and achieving goals of ecosystem management is less clear (Sumaila, 2010).

Towards Ecosystem-based Fisheries Management

While preindustrial fisheries had the capacity to extirpate some freshwater and coastal fish populations, as evidenced in the subfossil and archaeological records, it is only since the advent of industrial fishing that the sequential depletion of coastal, then offshore, populations of marine fish has become the standard operating procedure.

In the late nineteenth century, in the North Sea, where British steam trawlers were first deployed, it took only a few years for the accumulated coastal stocks of flatfish (and other groups) to be depleted, and for the trawlers to be forced to move on to the Central North Sea, then further, all the way to Iceland (Cushing, 1988).

Similar expansion processes are still going on, and this led, after the second World War, to massive increases of fisheries catches in the North Atlantic and the North Pacific, as well as in southeast Asia. By the late 1990s, the last large shelf areas previously not subjected to trawling had been depleted, as were most of the oceanic seamounts. All that is left for the expansion of bottom trawling is very deep (1–3 km) populations of demersal fish, whose extremely low growth rates, associated with lifespans of up to 150 years, essentially precludes sustainable exploitation. Hence, in the absence of legal protection, they are subjected to 'pulse-fishing' by distant water fleets of various industrial countries, that is, to rapid depletion of their biomass, without even the pretence of some form of responsible fishing.

Similarly worrying trends are occurring in open-water ecosystems, where long-lining for tuna and other large pelagic fishes depletes these systems of large predators, including sharks, now feeding an insatiable fin soup market. Also, purse seining around floating objects (i.e. natural or artificial fish aggregation devices) has made previously inaccessible small tunas and associated organisms vulnerable to fishing, thus prompting fears of the drastic decline of fish populations previously thought largely immune to our depredations. **See also**: Modern Extinction

The change in demersal and pelagic ecosystem structure resulting from such serial depletions is now widely known as "fishing down marine food webs" (Pauly *et al*., 1998). This concept illustrates that present catches increasingly rely on fish with low trophic levels, originating from the bottom of marine food webs, that is, on the prey of larger fishes, albeit without sparing or rebuilding the stocks of larger fish (Dulvy *et al*., 2014).

Ecosystem-based fisheries management instead requires leaving enough 'forage fish' for exploited populations of large predators, as well as for populations of protected marine mammals and birds (Pikitch *et al.*, 2014). Also, this will involve routine use of marine protected areas (MPAs) (with no-take zones at their core) to allow rebuilding and maintenance of now depleted populations of slow-growing fishes (Pikitch *et al.*, 2004).

Aquaculture, the farming of fishes and aquatic invertebrates, is viewed in some quarters as an alternative to fisheries as an approach for meeting the increased demand for fish products, thus obviating the need to improve fisheries management practices. However, this view does not take into account that globally, aquaculture (and especially the farming of marine fish) itself generates a huge demand for fisheries products, in the form of fish meals and fish oils, the key ingredients of aquafeeds (e.g. for salmon, a key mariculture species). Indeed, aquaculture is a net consumer of fish on all continents except Asia, where farmers still tend to rely on herbivorous species, although this seems to be slowly changing. Moreover, aquaculture production consumes even more energy (i.e. fossil fuel) than fisheries per amount of fish produced. Finally, mariculture operations (again, salmon culture provides the best example) have become major sources of coastal pollution (through fish faeces, and on-farm use of pesticides, antibiotics, etc.) and of escaped fish, which compete with the much reduced wild stocks (Naylor *et al.*, 2000). **See also**: Energy Use in Agriculture

Other Recent Developments

New developments in the twenty-first century involve various measures to implement ecosystem-based fisheries management (Pikitch *et al.*, 2004), notably through the creation of MPAs, and more recently, of very large marine reserves (Northwest Hawai'ian Islands, Chagos Archipelagos, Phoenix Islands, Pacific Remote Islands, etc.), and the creation of science-based networks of MPAs, such as in California (Gleason *et al.*, 2010), all now known to maintain biodiversity (Dulvy *et al.*, 2014) and resilience in an age where these are threatened (Roberts *et al.*, 2005). These new developments also involve an explicit consideration of trophic interactions, especially when small-pelagic (or 'forage') fish are concerned (Cury *et al.*, 2011). Perhaps more importantly, fisheries science again began to emphasise the rebuilding of depleted stocks (Murawski, 2010; Neubauer *et al.*, 2013; Rosenberg *et al.*, 2006), and the many benefits that can be derived from such rebuilding (Costello *et al.*, 2012).

Other new developments include the management of previously unregulated, data-limited stocks. The challenge here is to derive precautionary harvest limits from catch data and life history traits such as growth rates or rates of natural mortality (McCall, 2009). Surplus production models in combination with Monte Carlo approaches have been shown to be useful in this context, because only a surprisingly small subset of potential productivity and stock sizes, that is, the parameters from which MSY can be calculated, is compatible with an observed time series of catches (Martell and Froese, 2013).

Conclusion

Two distinct futures can be readily identified for fisheries management (Pauly *et al.*, 2003). The first would continue with business as usual, including the present trends of overcapacity and serial depletion of fish resources, as manifested by fishing down the marine food web. The other would lead to fisheries management integrating the establishment of annual TAC into a larger framework of ecosystem-based criteria for the operation of fisheries, including MPAs (with no-take areas at their core) as tools for resource conservation. Either future will have to deal with galloping fuel costs, which will lead to a restructuring of global fisheries away from fuel-intensive operations.

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