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Fishery Dynamics and Regulatory Policy

The dynamics of fisheries are reflected in collapsing fish stocks, idle fishing fleets and impoverished fishing communities. The economic and social costs of these dynamics are enormous. It has been estimated that on a global scale, the loss of economic rents (profits) due to mismanagement of fisheries may easily amount to 50 percent or more of the global landed value of the fish catch of some 100 billion US dollars annually[1]. If present trends continue then the industry's future is bleak. A report by a team of scientists and economists estimates that by the year 2048 fish stocks in *all* the world's main fishing regions will be close to extinction (Worm et al 2006). Already one third of fisheries have biologically collapsed and stocks could take decades to recover, even with a complete moratorium on fishing. It is a sobering thought that in less than 50 years there may be no commercial sea-fishing industry and no wild fish to eat on the table. The paradox of the fishing industry is that fishermen do not appear to act in their own best interests. They overexploit a renewable resource to the point of destruction, yet their livelihoods depend on a sustainable catch. It need not be that way.

Fisheries Management

Fisheries management is fundamentally a control and regulation problem, ensuring that collective fishing effort is well-balanced with available fish stocks and fish regeneration. Without any regulation fisheries tend towards bloated fishing fleets, excess effort, fish stocks that are too small, low profitability and low personal incomes. At worst fisheries collapse entirely. But why? An information feedback view suggests that fishermen do not receive a clear feedback signal from the fishery to tell them when to stop investing in ships and gear. This signal should be strong and credible at the point in time when collective effort (and therefore the catch) is approaching the highest regeneration rate the fishery can support (the so-called maximum sustainable yield). Regulatory policy should therefore be aimed at generating a 'correct' feedback signal to curtail over-investment and to ensure, with appropriate sanctions, that fishermen take notice and restrict the catch size.

In the following sections we augment the simple fisheries model from chapter one to illustrate the origins of the fisheries management problem and the feedback principles that lie behind effective regulation. The analysis involves a sequence of models that illustrate the challenges in coordinating fish stocks with the fleet size (and fishing effort). We begin with a simple model of fish population dynamics for a single species and demonstrate that sustainable catch increases with fleet size until a critical tipping point is reached. We then add a behavioural model of investment in ships to show the tendency for overexploitation in unregulated fisheries. Finally we add a new module to represent the monitoring, control and surveillance of fish stocks as the basis for regulation.

Economists have also studied the overexploitation of fisheries. They explain the paradox of bloated fishing fleets in terms of the 'common property problem' (Gordon 1954, Hardin 1968, Arnason 2005 and 2006). Ocean fish stocks have traditionally been arranged as common property resources, meaning that anyone with nets and a boat is able to harvest the resources. Under this arrangement it can be shown there are financial incentives to expand the fishing fleet (and effort) until costs equal revenues. At this special equilibrium point there are no profits left in the industry and the fish stock is depleted well below the biological optimum (and often dangerously close to collapse). Although this economic analysis does not investigate the *dynamics* of fish population and fleet expansion (focussing instead on feasible equilibria) it nevertheless sheds light on the decisionmaking of fishermen that leads them, collectively, to excess fishing effort. Regulatory policy is then seen as the design of fishing restrictions, quotas, property rights or taxes to inhibit investment and limit the catch. With appropriate incentives and sanctions an ideal equilibrium is envisaged in which the catch is sustainable and fishery profit is maximised.

Improving the management of fisheries is a big task but it can yield huge social and economic benefits. Ragnar Arnason (2006), an economist from the University of Iceland and expert in fisheries management notes that

> While mismanagement characterises the global fishery as a whole, it is important to realise that there are fisheries, sometimes quite sizeable fisheries, that do not adhere to this general pattern and are both biologically sustainable and highly profitable. These fisheries, which comprise such diverse marine conditions as those of New Zealand, Falkland Islands and Iceland, are in no way different from the other fisheries which exhibit declining stocks and negative profits. The only thing they have in common is good management. Generally, this management is based on high quality and well enforced property rights

Here we take a similar view that good fisheries management is vital to their long-term success, but we approach the topic dynamically from an information feedback perspective (Moxnes 1998).

A Simple Harvested Fishery - The Biological Problem of Balancing the Catch with Fish Regeneration

Cast your mind back to the very first simulator in the book. There we examined the dynamics of a simple natural fishery, free from human intervention –

just fish in the sea with no fishermen or ships. The result, over a period of 40 years, was smooth S-shaped growth as shown in figure 9.16. A small initial population of 200 fish (scaled for numerical convenience) grows exponentially for 18 years. Then over the next decade, as the fish stock approaches its maximum sustainable value of 4000, growth is halted and the fishery settles into a long-term equilibrium.

Figure 9.16 near here

Now imagine a harvested fishery. Ships arrive in the previously pristine sea and cast their nets. The total catch depends both on the number of ships and their productivity (how many fish each ship catches in a typical trip). Common sense suggests that if you add a few more ships to a small fleet then the catch will increase. Equally there must come a time when there are too many ships competing for a limited number of fish. We can use simulation to investigate the relationship between catch and fish population as fleet size varies.

A simple model of a harvested fishery is shown in figure 9.17 involving a fish stock, an inflow of new fish per year and a harvest rate. The corresponding equations appear below the diagram. Net regeneration is a non-linear function of fish density as indicated by the graph. The fish stock is depleted by a harvest rate, equal to the catch and proportional to the number of ships at sea.

Figure 9.17 near here

Consider a scenario spanning 40 years in which the fleet size starts at zero and then grows in stepwise bursts to reach a maximum of thirty ships. The productivity of these ships is identical. Bear in mind this is a scale model which can be calibrated to fit a realistic fishery without changing the pertinent dynamics. Each ship can catch 25 fish per year and for clarity we assume there is no stochastic variation in productivity. At the start there are four thousand fish. The fishery is full and the population is in equilibrium. Then, in year 4, ten ships sail into the pristine fishery and set about harvesting for the next 12 years. The simulated result is shown in figure 9.18. The catch (line 3) rises from zero to 250 fish per year. As a result the fish stock (line 1) begins to fall. But then something dynamically interesting happens. Because the fishery is less heavily populated, fish regenerate faster (as defined by the non-linear regeneration graph). As the years pass the number of new fish added to the population each year approaches ever closer to the harvest rate (and the catch) and so, by the end of year 15, the fish stock (line 1) settles into a sustainable harvested equilibrium.

Figure 9.18 near here

This pattern of bountiful adjustment is repeated as ten more ships are added in year 16. The catch (line 3) once again increases, this time reaching a value of 500 fish per year, just below the maximum sustainable yield. Gradually the regeneration rate rises to equal the catch bringing the fishery into a new and higher harvested equilibrium with a population of around 2,700 fish. However, in year 28, when a further ten ships are added to the fleet, the extra expansion pushes the catch beyond a tipping point that causes a rapid decline in the regeneration rate and the fish stock. The tipping point occurs at the peak of the non-linear relationship between net regeneration and fish density as depicted in figure 9.16[2]. Before the peak any reduction in fish density boosts regeneration. But after the peak any further reduction in fish density inhibits regeneration. The effect is clearly visible in the behaviour of new fish per year (line 2) which shortly before year 30, after more than two decades of growth, suddenly falls sharply to a value far below the catch (line 3). Even though the fishing fleet is later reduced to only 10 ships in year 34, (a fleet size that had previously yielded a sustainable catch) it is too late to reverse the fishery's decline and the fish stock collapses completely. Here in this dramatic switch of dynamic behaviour, from a robust sustainable catch to a fragile and declining catch, lies the key to the fisheries paradox.

A Harvested Fishery with Endogenous Investment - The Economic and Human Behaviour Problem of Coping with a Tipping Point

Investment in ships is a collective decision making process (or policy) representing, in aggregate, the judgements of those people most closely involved (fishermen in this case) and the information sources on which their decisions are based. Such decision making processes are behavioural in the sense that they capture the broad intention of investment without necessarily assuming decision makers have perfect information or perfect foresight. As we saw in chapter 7 (the market growth model) typical investment policy has three main parts: a goal for the intended capacity, monitoring of current capacity, and corrective action to bring capacity in line with the goal. This process of 'asset stock adjustment' applies equally well to investment in fishing fleets.

Figure 9.19 shows the investment policy for fleet adjustment in the fisheries model. Notice that connections between variables are depicted as dotted lines denoting flows of information. The connections are not 'hardwired' as they were for the natural fishery. They are discretionary and reflect the information available and deemed most relevant to investment. The desired fleet size (the goal) depends on the number of ships at sea and the propensity for growth. Specifically the desired fleet size is equal to ships at sea multiplied by a growth factor denoted as (1+ propensity for growth). We assume that the normal propensity for growth is 0.1, so the desired fleet size is 10 percent larger than the current fleet size. In other words fishermen normally and collectively want a bigger fleet than they now have, an attribute of human nature - bigger is better, growth is inherently attractive. This is an important behavioural assumption and recognises that fishermen lack the information (or even the inclination) to agree an optimal fleet size. They just want more and better ships. As we will see later the propensity for growth also depends on conditions in the fishery, a poor catch will dampen enthusiasm for a larger fleet, despite an underlying bias toward growth.

Figure 9.19 near here

The rest of the asset stock adjustment formulation is standard and straightforward, just like the formulations for inventory control and for employee hiring in chapter 5. The gap in fleet size is the difference between the desired fleet size and ships at sea. If there is a large positive gap then conditions for investment are favourable. The purchase or sale of ships closes the gap over an assumed time span of one year which is the time taken to adjust the fleet (including ordering, construction and delivery).

A crucial formulation in the model is the propensity for growth and the factors that determine it. As mentioned above fishermen do not know the optimal fleet size and so they prefer, more simply and pragmatically, to grow the fleet until there is compelling evidence to stop. In a real fishery the most persuasive information is catch per ship. Fishermen know this number from each fishing trip and it is vital to their livelihood. Significantly they do not know the fish population or the fish regeneration rate - because the fish are under water. Moreover they do not believe scientific estimates of low fish stocks unless confirmed by the catch. Such practical considerations suggest that propensity for growth is curbed by low catch rather than by objective evidence of fish stocks. As a result investment is boundedly rational, sensing only indirectly the true balance of the fish population on which the long-term sustainability of the fishery depends.

Figure 9.20 shows one possible formulation that captures the essential limited information characteristic of fishermen's boundedly rational decision making. Propensity for growth depends on the normal propensity for growth multiplied by the curbing effect of catch per ship. This curbing effect is non-linear and captures another typical human tendency: to ignore bad news until it is really bad. If catch per ship falls from 25 fish per year to15 per year (a 40 percent decline) propensity for growth falls from .1 to .09 (a decline of only 10 percent). Thereafter the effect becomes much stronger. If the catch per ship falls to 10 fish per year (less than half the normal value) then propensity for growth falls to zero and fishermen stop purchasing ships. If the catch falls still further then the propensity for growth becomes negative and fishermen sell ships because collectively they sense it is futile to retain a large and unproductive fleet.

Figure 9.20 near here

Catch per ship is essentially a measure of ships' productivity and is modelled here as a deterministic function of fish density. The scarcer are fish, the lower is productivity. But the relationship is non-linear. For moderate to high fish density (between .5 and 1) catch per ship remains close to normal. The assumption is that fishermen do not really notice a difference in the catch if the sea is teeming with fish or only half-teeming with fish, because fish tend to school or cluster. Catch per ship is still 68 percent of normal when the fish density is only .2, or in other words when the fish population is 20 percent of the maximum sustainable. But thereafter catch per ship falls quickly to zero as schools of fish become increasingly difficult to find and are hotly contested by rival ships.

An overview of the model with endogenous investment is shown in figure 9.21. In the top left quadrant is the natural fishery with its non-linear reinforcing loop depicting population dynamics. In the lower right quadrant is the fishing fleet. Investment is represented as a stock adjustment process in which a balancing loop adjusts the number of ships at sea and a reinforcing loop drives the desired fleet size. Fish biology and capital investment are linked through the catch, harvest rate and propensity for growth resulting in a dynamically complex non-linear feedback structure.

Figure 9.21 near here

Simulated Dynamics of a Harvested Fishery with Endogenous Investment

The model is initialised in a sustainable equilibrium with 10 ships and 3370 fish, resulting in a catch of 250 fish per year and equivalent net regeneration of 250 fish per year. This harvest rate is below the maximum sustainable yield to allow room for growth and to investigate the dynamics of boundedly rational investment. In order to start the model in equilibrium the normal propensity for growth is artificially held at zero during the early years of the simulation. It is as though a ‘small-is-beautiful’ mindset has temporarily taken hold of ship owners. Then in year 10 propensity for growth returns to its normal value of 0.1, or 10 percent of the current fleet size. The results are shown in figure 9.22. The reader can recreate this chart by running the model called Fish and Harvesting – Endogenous Investment in the CD folder for chapter 9. Set to zero the slide bar representing the normal propensity for growth. Then click the run button to see the first five years of equilibrium. Click the run button again to extend the equilibrium to ten years. Now reset the normal propensity for growth to its standard value of 0.1 by clicking on the ‘u’ symbol in the lower left of the slide bar. Then run the simulation all the way to 40 years.

Starting in year 10 the number of ships at sea (line 4) increases steadily. For fourteen years the catch rises. Meanwhile the catch per ship (line 5) remains steady, suggesting that continued investment is both feasible and desirable. Below the waves conditions are changing, but remember these conditions cannot be directly observed by fishermen. The regeneration rate of fish (new fish per year, line 2) rises, just as one would expect in a well-harvested fishery. The fish population falls, but that too is expected in a harvested fishery.

Figure 9.22 near here

Signs of trouble appear underwater in year 21 when, for the first time, regeneration (new fish per year, line 2) falls. This reversal of replenishment is a signal that the fishery has passed the tipping point of the non-linear regeneration curve. The decline in the fish stock begins to accelerate. But interestingly the catch (line 3) continues to rise for fully three more years, until year 24, and the catch per ship (line 5) remains close to normal. From the viewpoint of growth-oriented fishermen floating on the waves it is business as usual. The fleet continues to grow until year 26 when it reaches a size of 46 ships. By then the catch per ship (line 5) has fallen to less than one third of normal (only 8 fish per ship per year instead of 25), which is sufficiently low to curb further investment.

By now the hidden fish stock (line 1) has fallen to only 300, less than one tenth of its initial value. With so few fish in the sea the regeneration rate is precariously low at only 30 new fish per year, well below the catch of around 300 fish per year. Fishermen are now well aware of the underwater crisis and respond accordingly by selling ships. The fleet size (ships at sea, line 4) falls from a peak of 47 ships in year 26 to 39 ships in year 30. But it is too little action too late. The boundedly rational investment policy fails to reduce the fleet quickly enough to halt the decline of the fish stock. By year 30 there are only four fish left in the sea and regeneration has fallen practically to zero. The fishery has collapsed and is left with a huge excess of relatively new ships owned by fishermen reluctant to sell and still dependent on the fishery for their livelihood. The feedback structure of an unregulated fishery leads to boom and bust in the catch.

Control and Regulation – Policy Design for Sustainable Fisheries

The purpose of regulatory policy is to persuade fishermen to reduce their fishing effort when the population of fish is deemed to be too low. But how? This question is explored in figure 9.23 that shows the policy structure behind fishing effort. The fishing fleet is disaggregated to show both ships at sea and ships in harbour. A corresponding distinction is drawn between investment policy (whether to purchase ships) and deployment policy (whether to go fishing or to deliberately idle some ships in harbour). The concentric circles around these policies represent information filters, indicating that fishermen, as normal boundedly-rational decisionmakers, simplify complex (and often conflicting) information about the state of the fishery. Like everyone else they act on the basis of evidence from their own experience, paying most attention to signals that suit their local interests (For a reminder on information filters and bounded rationality, review chapter 7). We therefore continue to assume that investment decisionmaking is myopic, driven by the normal propensity for growth and the catch per ship as described above. Even when there is scientific information available about the fishery (shown in the grey region), it is not easy to inject this evidence into commercial decisionmaking. Incidentally if you think this is an unreasonable assumption then consider the difficult task for climate scientists in convincing us to travel less, or to turn down our thermostats, if we are to halt global warming. Like fisheries, global warming is a problem of managing the commons. And like fishermen we are reluctant to take scientific advice because the need to take immediate action is not compelling and the required changes in behaviour threaten our lifestyle.

Figure 9.23 near here

Regulation acts principally through deployment policy by requiring fishermen to reduce their fishing effort and/or to be selective in what they catch. In practice there are a variety of different approaches to regulation. For example there are biological restrictions such as mesh size regulations, total allowable catch, area closures and nursery ground protection. Alternatively there are economic restrictions on days at sea, fishing time and transferable quotas. Here we will focus attention on economic restrictions. In figure 9.23 deployment policy takes information, supplied to regulators by marine scientists, about fish density and optimal fish density. The regulators use this information to determine, on average, how many ships from the total fleet should be at sea and how many should be kept in harbour. This policy can be interpreted either as a limit on days at sea or a daily limit on fishing time.

But will fishermen pay any attention to these restrictions and the scientific information on which they are based? There is no particular reason why they should unless violations are noticed and punished. Effective fisheries management requires credible surveillance of ships' activities and strict enforcement of the rules backed by a judicial system capable of issuing sanctions to violators (Dudley 2003). Only then will scientific information about the state of the fisheries penetrate the filters of behavioural decisionmaking in figure 9.23 and lead to a more appropriate deployment of ships. Under schemes such as limited fishing days and closed areas it is necessary to monitor the fishing vessels' actual days at sea and their location when out fishing. The labour and equipment needed for such surveillance at sea is very expensive. In fact regulatory economists have estimated that the management costs of fisheries can be as much as 25 percent of the value of landings. In short a great deal of administrative effort lies behind successful fisheries management to ensure that valid scientific information is brought to bear, both forcefully and fairly, on fishing activity.

Formulation of Deployment Policy

Figure 9.24 extends the previous model of a harvested fishery to include the deployment of ships. The original formulations for fish population, fish regeneration, ships at sea and investment policy are shown on the left of the diagram. The new formulations for deployment and for ships in harbour are shown on the right. Deployment policy is subdivided in two stages: there is a recommended fleet size (shown as the shaded region on top) and there is surveillance of ships and enforcement (the shaded region below).

Figure 9.24 near here

The equations for deployment policy are shown in figure 9.25. The recommended fleet size is defined as the product of total ships and the sustainability index. The idea is to restrict the number of ships at sea if marine scientists think fish stocks are too low. Of course nobody knows for sure the actual number of fish in the sea. There are only estimates of fish density. Imagine that marine biologists monitor the fish population to arrive at an estimated fish density. In practice this is likely to be a time consuming process of compiling sonar data collected by biologists during missions at sea. It is modelled with a smoothing function (SMTH1) where the scientific measurement of density is captured in the ratio of fish stock to maximum fishery size, and the time to estimate fish density is half a year Armed with this sample evidence biologists then need to establish if the density is high enough to ensure a sustainable catch. If not then they will recommend limits on fishing. The benchmark for comparison is the assumed optimal fish density which is set at 0.6, corresponding to peak of the regeneration curve in figure 9.17. The sustainability index depends, non-linearly, on the ratio of the estimated fish density to the optimal fish density. When the ratio is in the range 1 to 1.2 (or more) the index takes a neutral value of one and there are no restrictions on the active fleet size. As the density ratio dips below 1, the index falls; gradually at first, but then very swiftly. For example if the density ratio is 0.8 (meaning that the estimated fish density is 80 percent of the optimal) then the index takes a value of 0.76 (meaning that the recommended fleet size is 76 percent of the total ships). But if the density ratio falls to 0.5 (meaning that the estimated fish density is only half the optimal) then the index takes a value of 0.03 (meaning that all but three percent of the fleet is supposed to be idled). This aggressive cutback acknowledges the fragility of the fishery around the tipping point.

Figure 9.25 near here

Surveillance of ships and enforcement together capture the pressures on fishermen to act on scientific advice. However, compliance may not be timely or complete and this inevitable foot-dragging is recognised in the equations. The number of ships moved to harbour is driven by the difference between ships at sea and recommended ships at sea. So if there are more ships at sea than recommended, the surplus is supposed to be idled. But some fishermen may cheat and ignore the recommendation. The scope for cheating is captured in the effectiveness of the fisheries management regime, a number that multiplies the surplus fleet. The parameter is set at 1 in the base case model, meaning that fishermen are completely honest. But the parameter can be varied on a scale from zero to 1 to explore the implications of weak management regimes in which only a fraction of surplus ships are idled. Even when the regime is presumed to be strong, redeployment does not happen instantly. In a given week or month only a fraction of the surplus ships are brought into harbour, according to the time to achieve compliance. This parameter is set at 0.5 years in the base case. So for example if there are 10 surplus ships (ships at sea – recommended ships at sea = 10) and no cheating (effectiveness of fisheries management regime = 1) then ships are moved to harbour at an initial rate of 20 ships per year (10/0.5), which is roughly 2 ships per month.

Stock and Flow Equations for Ships at Sea, Ships in Harbour and Scrap Rate

The remaining equations in figure 9.25 define the stock and flow network for ships. Ships at sea are represented as a stock that accumulates the difference between the purchase or sale of ships and ships moved to harbour. Initially there are 10 ships at sea. Ships in harbour are represented as a stock that accumulates the difference between ships moved to harbour and the scrap rate of ships. Initially there are no ships in harbour because, in the beginning, fish are abundant and the fishery is underexploited. The scrap rate of ships is formulated as the ratio of ships in harbour to the lifetime of idle ships. We implicitly assume that older ships are idled first and can be kept seaworthy for years. The lifetime of idle ships is set at 5 years in the base case.

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[1] Global landings from ocean fisheries have in recent years been in the neighbourhood of 84 million metric tones. Average landed value may be close to USD 1.20 per kg. Various empirical studies of fisheries around the world typically suggest loss of potential profits of some 50% of the value of landings.

[2] A thorough explanation of tipping points and the dynamics of 'quantity-induced' crises is to be found in Rudolph and Repenning 2002.