7 Strategic Interactions and the Environment

Many of the world's major environmental and natural resource management problems arise from interactions between economic agents. Examples include negotiations between countries about reducing greenhouse gases and marine fisheries where fishers compete with each other over fish stocks for profits. These types of interactions are recognized by economists and mathematicians as problems in game theory. Game theory can be applied to games such as chess and poker, but it can also be applied to make sense of the 'games' that governments, individuals, households, and firms 'play' that affect the environment.

This chapter:

- Introduces game theory.
- Discusses an important game called the prisoner's dilemma.
- Applies the basic model to fishery management.
- Considers how co-operation may emerge through institutions over time.
- Gives an analysis of the formation of alliances using co-operative game theory.
- Analyses a transboundary pollution problem.

7.1 Introduction

At local, international, and global levels, interactions between individuals, firms, and governments over environment goods and bads and natural resources involve strategic choices. Like chess players, the 'players' in environmental and natural resource 'games' develop strategies to counter their opponents' strategies. To start to understand these interactions requires a theory of strategic interaction between decision-makers. In 1944, a mathematician, John von Neumann, and an economist, Oskar Morgenstern, introduced game theory to economics. Their approach concerned players who take choices in response to or in anticipation of what others decide to do. Their models have revolutionized the analysis of strategic interactions between decision-makers from both normative (i.e. what decision-makers *should* do) and positive (what decision-makers *actually* do) perspectives (for an introductory review, see Dixit et al., 2009).

BOX 7.1 Cod Wars

In 1972 Iceland unilaterally extended its Exclusive Economic Zone (EEZ) beyond its territorial waters, in an attempt to exclude British trawlers and reduce overfishing. It policed its newly introduced catch quotas through the Icelandic Coastguard cutting the trawl lines of UK vessels. The UK responded by sending in naval vessels to protect the fishing fleet. The dispute ended in 1976 after Iceland threatened to close a major NATO base in retaliation for Britain's deployment of naval vessels within the disputed zone. The British government backed down, and agreed that after 1 December 1976, British vessels would not fish within the zone.

The interaction between the players (the UK and Icelandic governments) involves a set of strategies: Iceland plays 'send coastguard boats', to which the UK government responds with 'send the navy to protect trawlers'. Finally, Iceland plays its trump card, 'close NATO base', to which the UK responds 'concede'. What is driving these responses? The pay-offs are the economic gains to the UK of access to the fishery, whilst the pay-offs to Iceland are increasing the economic gains from a larger share of a better-managed fishery. In the final play, Iceland switches strategies, and in the threat to close a NATO base finds an action that would impose costs on the UK that exceed the losses in profitability of the UK fishing industry from access to the Icelandic EEZ. In this game, the two players interact repeatedly and the strategies evolve through time.

Economists have applied game theory to environmental and natural resource allocation problems. In one of the first applications, Levhari and Mirman (1980) analyse interactions between two countries sharing a fish stock, a so-called 'fish war' (see Box 7.1). The 'war' is waged through fisheries policies where fishery regulators decide to be more or less conservationist in their setting of fishing quotas depending on how conservationist they expect other countries to be. Countries impose an externality on each other by reducing the fish stock and thus making fish more expensive to catch. Another early application of game theory in environmental economics was by Maler (1989), who considers international negotiations to reduce the level of acid rain. When countries negotiate over the total levels of SO_2 emissions to be permitted, there is a strategic interaction in which countries benefit from co-operation (since acid rain has impacts in 'receiving' countries as well as in 'emitter' countries), but a mechanism has to be found to encourage those countries responsible for the externality to agree to a reduction in SO_2. Maler also found that a cost-effective solution to reducing European emissions would result in some countries incurring a net loss, and the countries with a net benefit paying them compensation. A third example is Agenda 21, agreed at the Rio de Janeiro Earth Summit in 1992 and recently renegotiated in Nagoya in 2010, which aims to protect biodiversity (Barrett, 1994a; Normile, 2010). Biodiversity represents a global public good, but the countries that benefit most from conservation may be the richer developed nations, while the less-developed tropical countries that host much of global biodiversity bear the opportunity costs of conservation through lost marine, agricultural, and forestry output. The issue is how an agreement can be reached that provides an incentive for these biodiversity host countries to reduce the rate of biodiversity loss.

Game theory has been applied to analyse national environmental problems; for instance, the strategic interaction between producers over a common-property resource such as common land grazing (Mesterton-Gibbons, 2000) and the interaction between regulators and the firms regulated in pollution control (Batabayal, 1995). The key element of all of these problems—both domestic and global—is that the actions of one decision-maker affect the welfare of others. All these problems are the subject matter of game theory.

7.2 Game Theory

7.2.1 Basic concepts

The elements of game theory are as follows. A decision-maker (player) has preferences over a set of outcomes, and these preferences determine the choices made, but the outcomes depend upon the choices made by the other players in the game. Game theory has developed two distinct approaches to analysing such problems. *Non-cooperative* game theory concerns how players choose strategies, whilst *co-operative* game theory concerns how players choose to form alliances. Non-cooperative game theory can be further classified into *static* and *dynamic* games, where static games have only one turn (one shot) and dynamic games have a number of turns through time. Dynamic games can be further subdivided into repeated games, where the same game is repeated, and more complex dynamic games, where the actual game itself changes through time.

Information, or the lack of it, determines how the game is played: games of *imperfect information* are those where the players are uncertain about the outcome of a combination of choices. For instance, in the fishing problem, uncertainty about the fish stock and harvest means that the profit is uncertain. Games of *incomplete information* are where players are uncertain about the preferences of other players. For instance, a regulator may be uncertain about the cost to a firm of complying with pollution regulation, and therefore be uncertain about an appropriate level of monitoring (Russell, 1990). Modern game theory makes use of advanced mathematics, and a general analysis is beyond the scope of this book. Fortunately, some simple models—for example, the prisoner's dilemma—offer insights into a wide range of environmental problems.

7.2.2 The prisoner's dilemma

The prisoner's dilemma is an important concept in environmental and resource economics. The original game, called the prisoner's dilemma by A.W. Tucker in 1950, has the following form. Two prisoners, Fred and George, have been caught with stolen goods and are suspected of burglary, but there is insufficient evidence to convict them unless one of them confesses. The police can convict both of them of the lesser offence of possessing stolen goods without further evidence. They are interrogated in separate rooms. The prisoners expect the following outcomes: if they both confess and agree to testify they both get 2 years in prison; if neither confesses they will both get a 6-month sentence; if one confesses, he will go free, while the other will get the maximum sentence of 5 years. The 'pay-offs' (measured as years in jail) from this situation are represented in the *strategic form* of the game given in Table 7.1. In each of the four cells, the pay-off to George is given first and the pay-off to Fred second.

Table 7.1 The prisoner's dilemma, strategic form

		Fred	
		Confess	Deny
George	Confess	2 years, 2 years	Free, 5 years
	Deny	5 years, free	6 months, 6 months

How might this game be played? George considers his options: if Fred denies burglary, then his best response is to confess, and go free, whilst if Fred confesses, then George's best response is still to confess. Therefore, George concludes that his best strategy is to confess, as it gives the best outcome whether Fred confesses or denies. We say that 'confess' is a *dominant strategy* and that the strategy 'deny' is *dominated*. Fred, following a similar line of reasoning, decides to confess as well.

This game has been of interest to game theorists and economists because in equilibrium both players are rational in the way in which they select their dominant strategy, but the resulting equilibrium outcome gives lower pay-offs to both players than they could have achieved had they both selected their dominated strategies; namely, 'deny'. Thus, if Fred and George had made a binding pact not to confess, before they were arrested, both players would be better off compared with the dominant strategies. Co-operation requires either trust or some other mechanism that enforces a co-operative outcome. This is the essence of the prisoner's dilemmas that arise in environmental economics: an optimal solution is often rejected because of distrust or a lack of co-operation between players. Examples of prisoner's dilemmas from natural resources and environmental economics include the following:

- Countries that impose an acid rain problem on each other would both be better off collectively if they could agree to curtail sulphur dioxide emissions. Without agreement, it is individually rational for a country to only account for its national external costs instead of international external costs—that is, for the damages it imposes on others as well as itself.
- Countries are reluctant to sign global agreements to cut greenhouse gases, since the actions of others to reduce emissions deliver benefits to non-signatories and signatories alike.
- Urban dwellers who suffer from congested roads and air pollution would be collectively better off if they used their cars less, but it may still be rational for individuals to not change their pattern of car use.
- Sheep farmers sharing common grazing land degrade the land by overstocking because they cannot agree to binding reductions in stocking rates.
- Fishers, who share a common-property marine fishery, overfish because they cannot devise a way of sharing the benefits of conservation.

How does the dilemma arise? In the acid rain example, the lack of property rights concerns air quality: neither country has a right to control international air quality, even though it may be in their interests to agree on improvement. Similarly, collective action to limit car use is often beneficial, but there is a public good aspect to this (see Chapter 2): good air quality is a pure public good, since it is non-rival and non-excludable. Thus, there is little incentive for an individual to voluntarily limit his or her car use unless he or she could be sure that everyone else would do the same. Fisheries and common land grazing are overexploited because they are either common property (shared by a group of owners), or open access, owned by all (again, see Chapter 2). The problem is conventionally seen as one of an absence of, or shared rights over, a resource where each firm imposes an externality on other firms who share the resource. We now consider the last of these examples in more detail and give a brief introduction to fishery economics.

7.2.3 **Common property—the fisher's dilemma**

Currently, many of the world's major marine fisheries are in a state of either full exploitation or depletion (FAO, 2008: 7). The terms 'full exploitation' and 'depletion' are defined in relation to the maximum catch that is possible without depleting the fish stock, termed the *maximum sustainable yield*. 'Fully exploited' indicates that the catch is approximately equal to the maximum sustainable yield; 'depletion' indicates that the catch exceeds the maximum sustainable yield. Many economically important fisheries, such as the Grand Banks cod fishery, have been closed to commercial fishing (Kurlansky, 1999). In this section, we offer an explanation, based on game theory, of how the problem has arisen, but before that we provide an economic model of fishing.

The fishery model has a biomass growth function—the biological growth of the fish stock—and a relationship giving catch as a function of fishing effort (a measure of all the inputs used in fishing, such as the number of boats and the hours at sea) and the stock. To simplify the model, we assume that the fishery is always run in a 'steady state' where the catch equals biomass growth; this means that the stock remains constant. This allows us to derive a relationship between the catch and the harvest effort that does not include the stock, but accounts for the effect of stock size on the catch per unit of fishing effort. In fishery economics, this is called the yield–effort curve.

In any fishery, the key relationship is how the fish stock changes through time; that is, the growth function. In our model, fishers share a fishery in which the stock of fish changes through reproduction, mortality, and growth according to a logistic growth curve given by

$$g(x) = \gamma(1 - x/K)x. \tag{7.1}$$

In biology, this is a standard way of representing the growth of a population. Here, $g(x)$ is the growth function, which gives the rate of stock growth per unit of time; x is the stock of fish, in tonnes; γ is a growth parameter; and K is the carrying capacity of the marine ecosystem. The parameters can be interpreted as follows: the growth parameter, γ, gives the rate of change of the stock when the stock is very low (close to zero). In that case, the rate of stock growth is approximately γx. Thus if $\gamma = 0.5$, the rate of stock growth is equal to half the stock per period. At higher stock levels, the term $(1 - x/K)$ acts to reduce the growth rate, until the stock reaches a carrying capacity K and the growth rate is zero. The carrying capacity is the maximum biomass of a given species that the ecosystem can support. Note that if $x = 0$, then $(1 - x/K) = 1$; and if $x = K$, then $(1 - x/K) = 0$.

The firm's catch (qi) is given by the following function:

$$q_i = \theta h_i x. \tag{7.2}$$

In economics, this is a production function in which there is a relationship between inputs, fishing effort h_i (measured, for example, as a number of standard trawler days at sea) by fishing firm i and the stock of fish. Later on, we allow for the possibility that there is more than one fishing firm. The other parameter, θ, represents how easy fish are to catch. Note that this equation can rearranged so that $q_i/h_i = \theta x$; that is, the catch per unit of effort is proportional to the stock size: the larger the value of θ, the easier fish are to catch. This relationship also encompasses the status of technology in the fishery, as new fishing technology makes the fishing effort more effective by increasing the value of θ. An important aspect of the production function is that the catch of fish for a given harvest effort depends upon the fish stock; if there are more fish, it is cheaper to catch a fish.

We now bring together fish biomass growth with harvesting. We do this by assuming that the fishery operates in a 'steady state equilibrium', where the quantity of fish caught equals the growth in biomass. Thus:

$$g(x) - q_i = 0.$$

Substituting in equations (7.1) and (7.2), the above steady state equation can be written as follows:

$$\gamma x(1 - x/K) - \theta h_i x = 0,$$

and by solving for x and substituting back into equation (7.2), we obtain the yield effort curve:

$$q(h_i) = \theta h_i K(1 - \theta h_i/\gamma) \tag{7.3}$$

(see Box 7.2 for the derivation). This is a modified version of equation (7.2) that accounts for the steady state of stock.

We have described the technical aspects of a simple fishery, so now we introduce prices and an expression of profit to define an economic problem. First, if we multiply the catch by a constant price p, we obtain the equation *total revenue* $= pq(h_i)$. If we multiply the fishing effort by the cost per unit of fishing effort, we obtain the total cost: *total cost* $= wh_i$, where w is the cost per unit of fishing effort measured as the cost of a trawler day. Profit is the difference between total revenue and total cost:

$$\pi_i = pq(h_i) - wh_i.$$

To maximize profit, the firm equates the marginal revenue per unit of harvest with the marginal cost of harvest at h^s in Figure 7.1. This represents a social optimum where the marginal revenue from fishing equals the marginal social cost. If a regulator were to choose how to manage a fishery to maximize, then a total harvest effort of h^s is likely to be optimal. It is the maximum level of profit that the fishery can generate, and if firms were able to co-operate, they would choose this level of harvesting and share the profit.

However, in an open-access fishery any firm can enter the fishery, attracted by the profits of those already fishing there. This is a common situation in many of the world's fisheries. The harvest effort increases by firms continuing to enter the fishery until the profits are driven down to zero, at which point there is no longer an incentive for additional firms to enter. This occurs where effort is h_∞, total revenue equals total cost, and profit is zero. Open access results in too much fishing effort and too few fish left in the sea.

7.2.3.1 **A Nash equilibrium with two firms**

We have now set up a simple economic model of a fishery and analysed two extremes: one profit-maximizing firm and a number (possibly a very large number) of firms that drive the profit down to zero. Now we consider an intermediate case where the resource is shared by two firms and there is no agreement between them to co-operate. Assume that there are two identical firms who share the fishery, thus their production functions are identical:

BOX 7.2 Derivation of the Nash Equilibrium for a Fishery

Read this box if you would like to understand how the Nash equilibrium is derived. Taking the yield effort curve shown in equations (7.1) and (7.2), if there are two identical firms in the fishery, the steady state total quantity caught is as follows:

$$x\gamma(1 - x/K) - \theta xh = 0.$$

Solving for x gives $x = f(h) = K(\gamma - \theta h)/\gamma$ and the yield effort curve—that is, the catch as a function of the harvest effort only (with the stock eliminated)—is:

$$q = \theta hK(\gamma - \theta h)/\gamma.$$

For two firms, $h = (h_1 + h_2)$, that is total effort in the fishery, using this definition, **(Unclear.}** we give the stock as a function of the total harvest $f(h)$. For more than two firms, the harvest of all other firms is given by h_{-i}; thus the total harvest is $h = h_i + h_{-i}$. If this is substituted into the firms' profit functions:

$$\pi i = p\theta h_i f(h) - wh_i,$$

and the firms are linked together by the shared stock through the term $x(h)$. The Nash equilibrium for firm i is defined where

$$\frac{d\pi_i}{dh_i} = p\theta(f(h) + hf'(h)) - w,$$

where the derivative $f(h) = -\theta K/\gamma$.

This gives the response of firm i as

$$h_i = \frac{Kp\theta\ (\gamma - h_{-i}\ \theta) - w\gamma}{2Kp\theta^2}$$

This Nash response curve is given in Figure 7.2.

If there is a single firm,

$$h_i^c = \frac{\gamma(Kp\theta - w)}{2Kp\theta}$$

The two firms will continue to adjust their fishing effort along their response curves until the derivatives of both firms are zero:

$$h_i^N = \frac{\gamma(Kp\theta - w)}{(3Kp\theta)}$$

Define

$$\kappa = \frac{\gamma(Kp\theta - w)}{(Kp\theta)}\ .$$

The total fishing effort with both firms following a Nash strategy is

$$h^N = (2/3)\kappa.$$

With a single firm, the total effort is $h^C = (1/2)\kappa$. This gives the first result: the single-ownership firm always puts in less total harvest effort than the two competing firms, the stock from equation (a) is reduced, and the quantity caught may or may not be reduced. Finally, the total cost is $c = w(q/\theta x)$; thus reducing the stock increases the average cost of catching fish.

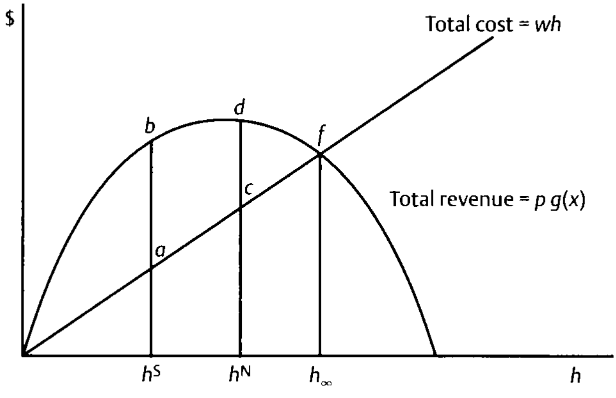

Figure 7.1 Fishery revenue and cost curves.

$$\pi_1(h_1 \mid h_2) = pq_1(h_1 \mid h_2) - wh_1; \qquad \pi_2(h_2 \mid h_1) = pq_2(h_2 \mid h_1) - wh_2.$$

The important point to note about these equations is that the profit of firm 1 is affected by the harvest of firm 2, and vice versa. For instance, the term $q_1(h_1 \mid h_2)$ indicates the catch of firm 1 *given* the fishing effort of firm 2. The form of this problem allows us to introduce the Nash equilibrium, a fundamental equilibrium concept in game theory. The profit of one firm acting independently depends upon what the other fishing firm does; therefore, the best a firm can achieve is to take the strategy of the other firm as given and maximize its profit on that basis. To reach a final equilibrium, firms may iterate towards a point at which neither firm wants to change.

If we choose some specific parameters for the fishery model: $K = 1000$, $\gamma = 1$, $\theta = 0.1$, $w =$ \$2,000 per unit of effort per month, and $p =$ \$10,000 per tonne of fish, we can produce the pay-off matrix shown in Table 7.2.

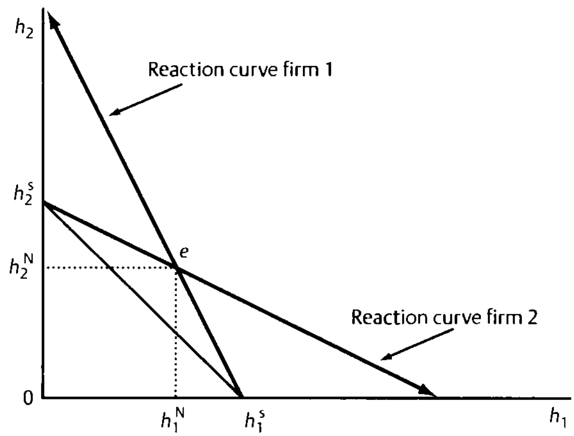

Figure 7.2 Fishery Nash equilibrium.

Table 7.2 The fisher's dilemma

		Firm 2 ($ million)	
		Nash (compete)	Co-operate
Firm 1 ($ million)	Nash (compete)	1.07, 1.07 NN_1, NN_2	1.35, 0.9 NC_1, NC_2
	Co-operate	0.9, 1.35 CN_1, CN_2	1.2, 1.2 CC_1, CC_2

By considering Table 7.2 with Figure 7.2, we see that the Nash equilibrium represents the best response to the other player's expected strategy. However, if both firms were able to co-operate, possibly through negotiated agreement, they would both be better off by $133,389. The Nash equilibrium is thus not optimal from the economy's point of view. Shifting the solution from the Nash equilibrium to a co-operative solution is said to be Pareto optimal, in that two firms are made better off and no firm or individual is made worse off. From Figure 7.2, the harvest rates h_1^s and h_2^s are the profit-maximizing efforts that the firm would choose if they had single and exclusive ownership of the resource. Reaction curves give the Nash response of one firm to the other firm's harvest effort; that is, they give the profit-maximizing harvest effort given the other firm's harvest effort. A Nash equilibrium occurs at *e* with an effort of $h_1^N + h_2^N$. At this equilibrium, there is no incentive for the firms to choose another strategy. The line from h_1^s to h_2^s shows a range of optimal 'co-operative' solutions. Along this line, the harvest effort is chosen so that firms maximize their *joint* profits. The total Nash equilibrium fishing effort, $h_1^N + h_2^N$, is greater than under single ownership, but the profit is less: therefore, this represents an inefficient outcome, as noted above. The solution is also illustrated in Figure 7.1, where $h^N = h_1^N + h_2^N$. Note also that the fish stock is greater under the profit-maximizing harvest at h^s. A fishery regulator should prefer the profit-maximizing solution, as it gives the greatest total welfare to producers and is therefore efficient. In a more general model, it would also maximize welfare to the economy as a whole—that is, producers and consumers—from the fishery.

There are two key results that emerge from this analysis. First, if the two firms co-operate, they stand to benefit by increasing their profit. The second point is that the problem of sub-optimal exploitation becomes worse as the number of firms increases, until the open-access equilibrium is reached, at which all firms earn zero profits. This gives a game-theoretic interpretation of Hardin's (1968) 'tragedy of the commons'. A prisoner's dilemma characterizes the outcome for two or more firms, but the problem becomes more severe when there are a large number of firms. With a small number of firms, a co-operative outcome may emerge as an equilibrium, especially when the game is repeated a large number of times. We discuss this further below.

7.3 Self-governance—Escaping the Tragedy of the Commons

In his paper 'The tragedy of the commons', Hardin (1968) foretells of dire consequences for common-property resources. However, the situation he is describing is more akin to open-access than limited-entry common property. Using common grazing as an example, Hardin predicts that:

> Each man is locked into a system that compels him to increase his herd without limit—in a world that is limited. Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons. Freedom in a commons brings ruin to all.
>
> (Hardin, 1968: 1244)

A different view is offered by Elinor Ostrom (1990), who won the 2009 Nobel Prize for Economics for her work on common-property resources:

> Elinor Ostrom has challenged the conventional wisdom that common property is poorly managed and should be either regulated by central authorities or privatized. Based on numerous studies of user-managed fish stocks, pastures, woods, lakes, and groundwater basins, Ostrom concludes that the outcomes are, more often than not, better than predicted by standard theories. She observes that resource users frequently develop sophisticated mechanisms for decision-making and rule enforcement to handle conflicts of interest, and she characterizes the rules that promote successful outcomes.
>
> (Nobel Prize Committee, 2009)

Ostrom (1990) observed that a significant number of common-property resources have avoided the tragedy of the commons as a result of users developing institutions that increase the efficiency of resource exploitation. She argues that the predictions of the prisoner's dilemma and, more generally, Nash equilibrium are not an inevitable outcome for common-property resources, because the potential exists for communication between players before they take their decisions. Government intervention is one way of forcing producers to co-operate, but this is not necessarily the only way.

In one alternative, firms may be able to co-operate by agreeing to abide by the decisions of an external regulator or referee, who may even be appointed by the firms and paid a fee. The referee acts by imposing penalties to ensure that the firms do not play their Nash strategies. This offers an escape route from the inefficient Nash equilibrium and thus from the prisoner's dilemma. Firms now have an incentive to co-operate so long as each firm's share of the fee is less than the difference between the co-operative solution and Nash equilibrium, which is $(1.2 - 1.08) = 0.12$ from Table 7.2. The penalty agreed by the firms should be large enough so that there is no incentive to cheat on the agreement; for instance, an amount greater than the difference between the profit rates—that is, $133 thousand—should give an adequate incentive, especially if non-compliance is always detected.

Ostrom (1990) found that voluntary institutions work effectively in managing common-property resources where a relatively small number of firms share the resource. Common-property institutions tend to break down when the number of firms involved increases, or when there is a lack of family and community ties between the appropriators of the resource. Examples of where voluntary institutions have been successful include Turkish inshore fisheries (see Box 7.3), lobster fisheries in Maine, and irrigation schemes in the US Midwest (Ostrom, 1990).

7.4 Repeated Fishing Games

In Section 7.3, we concluded that the mismanagement of common-property resources is not inevitable. Some shared resources have been well managed without private ownership.

BOX 7.3 An Example of Self-organization in a Common-property Resource

Bodrum is located about 400 km west of Alanya on the Aegean Sea. The inshore fishery (Berkes, 1986) is relatively small, with about 100 local fishers operating two- to three-person boats. In the early 1970s, the fishery was in a depressed state. Conflict existed amongst the local fishers due to unrestrained access to the fishery, and local fishers devoted resources to competing for the best fishing spots, which tended to increase production costs.

In response to this situation, members of the local fishing co-operative began to experiment with a system for allotting fishing sites. After almost a decade of refinement, the resulting system is as follows.

Each year, a list of eligible fishers is drawn up. The fishing locations are named and listed. In September, the fishers draw lots and are assigned a location, but on each day of the fishing season, from September to May, they shift east to the next location. This gives the fishers equal opportunities to catch the migratory fish stock.

This system means that no resources are wasted by the fishers fighting over preferred locations; and the system is self-policing, with the fishers enforcing the system themselves by reporting fishers who are in the wrong location. The fishery is managed efficiently with the tacit support of the Turkish government, but no direct policy intervention.

One other explanation is that the players are brought together in long-term competition rather than a single 'one-shot' game such as that analysed in our simple fishing example. Over time, players may develop a system of sharing the resource by agreement, but agreement would only come about because the firms expect to benefit in the long term from showing restraint. This describes a repeated game where a sequence of games is played through time. Repeated games have a much larger number of potential strategies than one-shot games. There is the potential for observing how the other firms play over time, and for tacit agreements to co-operate or punish to emerge. If the prisoner's dilemma is played a large number of times, then co-operation can emerge as equilibrium. This equilibrium is reinforced by the threat that if one player stops co-operating, everyone will be punished by a return to a disadvantageous non-cooperative equilibrium. This is called a 'tit-for-tat' strategy, and it was found by Axelrod (1984) to be a frequently selected strategy in experiments where people play repeated prisoner's dilemma games.

In many real strategic interactions, such as water resource sharing or negotiations over fishing rights, games are repeated over and over again. It is an equilibrium to 'confess' in the one-shot prisoner's dilemma, because there is no possibility of repercussions at a later stage of the game. The key result in this literature is that when a game is repeated many times, co-operation may emerge as a competitive equilibrium. However, if the game is repeated just a few times, then the equilibrium is the same as for the one-shot game. If the game lasts only a few turns, then the players will reason as follows: in the last stage of the game, the other player has no incentive to do anything other than not co-operate, because in the last stage we have a one-shot game. On this basis, moving to the previous stage, there is no scope for retaliation, so the player chooses a Nash strategy and so on, back to the start of the game. Thus in this finite game we conclude that the outcome is to play the Nash strategy in all periods. If the game is repeated indefinitely, discounting ensures that the final period is of no importance, but the prospect of retaliation is important—in the sense that the optimal outcome is a policy where each player co-operates until the other deviates and then deviates for the remainder of the game. The reason for this is that the most the player can gain from deviating is a one-period improvement in his or her pay-off, which is followed by a reduction in pay-offs for the remainder of the game.

Consider what happens if the fisheries game in Table 7.2 is repeated a large number of times and the players adopt a tit-for-tat strategy. The pay-offs from the fishery game from Table 7.4, where CC_1 indicates that both firms co-operate and gives the pay-off to firm 1, CN_2 indicates that firm 1 co-operates while firm 2 plays a Nash strategy and gives the pay-off to firm 2. The present value of firm 1 co-operating for a long time is discussed in Box 7.4.

For the firms to gain by deviating, this equation would have to be positive. The gain from deviating lasts for only one period, when they receive $(NC_1 - CC_1)$, but they are then penalized for all periods after that $(NN_1 - CC_1)$. The present value of punishment forever is $(NN_1 - CC_1)/r$, where r is the discount rate (see Box 7.4). From this, it is obvious that

BOX 7.4 Revision on Discounting

How do we evaluate decisions that give costs and benefits over time? The problem is that \$1 today is worth more than a \$1 in a year's time, because we can invest that \$1 in the bank or in the stock market and earn interest. So when evaluating a flow of net benefits (benefits minus costs), we cannot simply sum the net benefits in each year to give a total net benefit. This total would not take account of the lost investment opportunities. Instead, we calculate the present value of net benefits, which converts \$1 in future years to its value today. For instance, if we compare \$1 today with \$1 in a year's time, the value of \$1 in a year's time needs to be adjusted downwards to account for the fact that \$1 today can be invested and earn annual interest equal to r. Let us suppose that $r = 0.1$ (10%). Then, after a year, \$1 equals $(1 + r) \times 1 = 1.1$. The relative value of \$1 after a year is, therefore, $(1/(1 + r)) = (1/1.1) = 0.9090$. In other words, the present value of \$1 after a year is about 91 cents. After 2 years of compound interest, the dollar now has grown to $(1 + r)^2 \times 1 = 1.21$, the relative value of a dollar after 2 years is $(1/(1 + r)^2) = 0.8264$. A general value for the discount factor is $\delta^t = 1/(1 + r)^t$, where δ is the discount factor and t is the number of years into the future.

If a resource or an environmental asset is expected to give a constant flow of net benefits (y_t) for the foreseeable future, then we can actually simplify the discounting formula. The present value of a flow of income is given by

$$PV_T = \delta^1 y_1 + \delta^2 y_2 + \ldots + \delta^T y_T.$$

If the income is constant, then the present value can be given as

$$PV_T = \delta^1 y + \delta^2 y + \ldots + \delta^T y.$$

We can rewrite this geometric progression as

$$PV_T - \delta^1 PV_T = \delta^1 y - \delta^{T+1} y$$

or

$$PV_T = y(\delta^1 - \delta^{T+1})/(1 - \delta^1).$$

Note that if $T = \infty$, $\delta^{T+1} = 0$, and thus

$$PV_T = y(\delta^1)/(1 - \delta^1) = y/r.$$

Therefore, the present value for a constant income over an infinite period is simply the net benefit divided by the discount rate.

deviating from co-operation only pays if the benefits of deviating are very high or the discount rate is very high. For the example given in Table 7.2, the gain from deviation is $(1.35 - 1.20) = 0.15$, but the punishment is $(1.20 - 1.07)/r$. The discount rate would have to be 80 per cent ($r = 0.8$) for deviation to be worthwhile, which implies a very low weight on future pay-offs. A typical discount rate even for a highly impatient individual would probably be less than 20 per cent.

7.5 **Co-operative Games**

Co-operative games are concerned with the formation and stability of coalitions. For instance in a European Union negotiation over sharing out EU fishing quotas, if France and Spain form an alliance and agree to work together to get a bigger share of the quotas in negotiations with other countries and coalitions of countries, this is an example of a co-operative game. Forming an alliance is a strategy. History also tells us that such alliances are not always stable. The fact that co-operative game theory focuses on alliances as strategies tends to simplify the description of the details of the rest of the game; for instance, how much fish is caught by France and Spain. Instead the focus is on the total pay-offs of a coalition.

Co-operative games arise where, for instance, instead of competing, players decide to establish coalitions. In relation to a common property, a group of fishers or graziers may decide to form a group or coalition that determines how the resource is shared. More formally, co-operative games arise where players can form binding agreements in pre-play negotiations. Strictly, co-operative games are a special case of non-cooperative games, in that a non-cooperative game can be extended to include the decision to form a coalition in which a group of players play as if they are single players. This could occur between fishers within a producer's co-operative, where they negotiate collectively for fisheries quotas and licences, but they then need to decide how they share the gains between co-operative members. Co-operative game theory focuses on the pay-offs that different 'coalitions' can achieve, rather than on the details of how the game might be played. The following is a non-technical account of the basics of co-operative game theory with reference to the following example (for more detail, see Hanley and Folmer, 1998).

Suppose that three countries share a groundwater reservoir. They have a choice of acting individually or collaborating in various coalitions, including a 'grand coalition' that includes all countries. Each country receives the pay-off indicated in Table 7.3.

Table 7.3 The groundwater co-operation game

Coalitions of countries	Value of coalitions ($ million)
A	10
B	20
C	30
A, B	50
A, C	60
C, B	70
A, B, C	100

Table 7.3 gives the pay-offs to different combinations of countries. Let us define a pay-off function, $v(.)$, that gives the value of the game to various coalitions; for instance, $v(\{A\}) = 10$ gives the value to country A resulting from 'going it alone', $v(\{A, B\}) = 50$ gives the pay-off from a coalition between countries A and B, and so on. The next question is which coalitions of players are likely to form. For instance, $v(\{A, B\}) = 50$ indicates that a coalition between A and B has a pay-off of 50 units, while the grand coalition has a pay-off of 100, and thus $v(\{A, B, C\}) = 100$. Therefore, in this game the grand coalition gives a bigger pay-off than all sub-coalitions, but we have to check whether the coalition is stable. In other words, do either A, B, or C have an incentive to leave the grand coalition?

Now that we have set out the basic structure of co-operative games, it remains to discuss solution concepts that determine how players divide the benefits of co-operation. The approach to this is to assume that the grand coalition forms and then assess if a pay-off $\pi(S)$ (where S is a single player or a group of players) can be set that provides an incentive for the coalition to continue. The first condition is a 'budget constraint':

$$\pi(A) + \pi(B) + \pi(C) = v(\{A, B, C\}) = 100.$$

This ensures that the pay-off is shared amongst the players. Next, we need to specify individual and group (or coalition) rationality. This assesses whether players are able to achieve higher pay-offs outside the grand coalition, either individually or in other coalitions. Individual rationality says that $\pi(A) \geq v(\{A\})$; in other words, the pay-off received by country A as part of the coalition must be no less than the amount that country A could achieve alone. This extends to group rationality as $\pi(\{S\}) \geq v(\{S\})$: thus the pay-off to the subset of players S under the grand coalition must be greater than the pay-off that could be achieved by S as a separate coalition, $v(\{S\})$.

Individual and group rationality defines a set of constraints on pay-offs that would be acceptable to all players. The set of all such pay-offs that satisfy individual and group rationality is called the *core* and sets of pay-offs are called *imputations*. These concepts can be illustrated for our specific game using a diagram. Figure 7.3 shows the shares of the grand coalition as a triangle. In each corner, one player receives a pay-off of 100 and the others nothing. The lines across the triangle indicate individual rationality. For instance, $v[\{A\}] = 10$; thus in

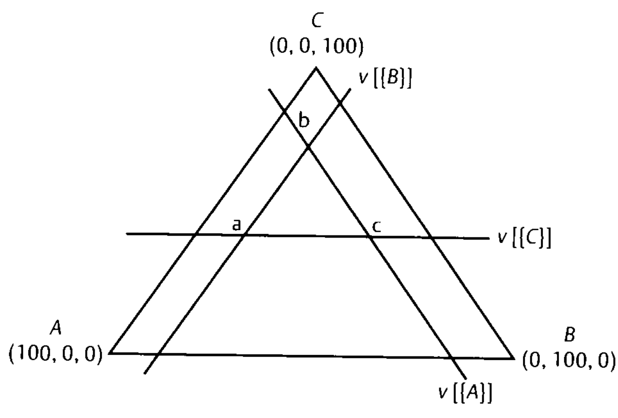

Figure 7.3 The co-operative solution: individual rationality.

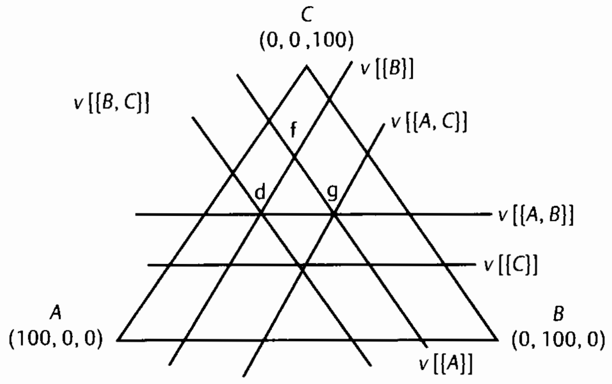

Figure 7.4 The co-operative solution: individual and group rationality.

terms of individual rationality, *A* must receive a pay-off of at least 10 due to individual rationality, which leaves 90 units to share between *C* and *B*. The smaller triangle *abc* is the set of pay-offs that satisfies the individual rationality constraints. Turning to Figure 7.4, we now introduce the group rationality constraints as well as the individual rationality constraints. This accounts for the pay-offs that the countries can obtain in sub-coalitions. The core *dfg* of the game represents a set of possible pay-offs that satisfy both the individual rationality and group rationality constraints. The actual solution would be determined by negotiation between the players and relative negotiating power (see also Box 7.5).

Co-operative game theory is a useful tool in environmental and natural resource economics, as it helps to explain why groups with similar preferences form alliances and agree to negotiate together. For instance, alliances have tended to emerge in global climate change negotiations in Cancun and Copenhagen between countries with similar interests (see Chapter 12). It also allows us to analyse how stable these alliances are and which alliances may form in the future.

7.6 Game Theory and Transboundary Pollution Control

7.6.1 **Introduction**

Transboundary pollution concerns emissions that cross international boundaries. We choose to analyse this problem here because it includes elements of both co-operative and non-cooperative game theory. Non-cooperative game theory analyses the outcome in the absence of negotiation, whilst co-operative game theory analyses how countries form coalitions and how stable these coalitions are. Transboundary pollution problems are of three broad types:

- First, there are unidirectional externalities, where an 'upstream country' affects a 'downstream' country. This form of externality is characterized by water pollution, where a country pollutes a river and hence imposes costs on the downstream country.
- Second, regional reciprocal externalities are typical of public goods such as European air quality, as measured by SO_x and NO_x levels. The actions of a country affect not only its own costs or benefits, but have impacts in other countries as well: emissions of

BOX 7.5 Self-enforcing International Environmental Agreements

International environmental agreements (IEA), such as the Montreal Protocol, for ozone-depleting substances and the Kyoto Protocol to limit emissions of greenhouse gases, have been characterized by protracted negotiations and partial agreements. The lack of a 'higher authority' makes international environmental agreements difficult to negotiate and police. Barrett (1994b, 2005) proposes that international environmental agreements should be self-enforcing, which means that the group of countries that sign the agreement have no incentives to leave the agreement and those that are non-signatories have no incentive to join. The condition for self-enforcement for a group of N identical countries is similar to the group rationality constraint from co-operative game theory. Countries divide into signatories (s) or non-signatories (n) to an IEA such that $N = n + s$. A coalition of signatories is stable if the following conditions are satisfied:

incentive to leave the agreement: $\pi_n(n+1) \leq \pi_s(s)$; (1)

incentive to join the agreement: $\pi_n(n) \geq \pi_s(s+1)$; (2)

where the pay-off to signatories is $\pi_s(s)$, and the pay-off to non-signatories is $\pi_n(n)$. A coalition is stable if there is no incentive for a country to accede to the IEA and no incentive for a country to leave. Condition (1) above says that there is no incentive to leave the coalition because the pay-off to a signatory is greater than the pay-off to a non-signatory when the number of non-signatories is increased by 1. Condition (2) says that there is no incentive to join, as the pay-off to a non-signatory is greater than a pay-off to a signatory when the number of signatories is increased by 1.

The implications of this theoretical model are rather depressing. They imply that self-enforcing IEAs only include a large proportion of the countries when the benefits of co-operation are relatively small. Where the benefits of co-operation over non-cooperation are large, then the equilibrium tends to include only a relatively small proportion of the countries. The implication of this result is that it is going to be very difficult for countries to agree to IEAs, and we may see partial agreements where one group of countries joins and another group remains outside the agreement.

sulphur oxides from the United Kingdom acidify UK lakes and streams, but also impact on Swedish and Norwegian lakes and streams (see Box 7.6).

- Third, global externalities are subdivided into those that involve physical interactions between countries and those that do not. For instance, by thinning the ozone layer, chlorofluorocarbon emissions have the potential to cause detrimental health effects on most of the human population. Likewise, greenhouse gas emissions will, through global warming, affect everyone (see Chapter 9). Non-physical effects relate to a range of goods with non-use values. These bring in issues related to the conservation of global biodiversity (see Chapter 12).

All of these pollution problems involve a strategic interaction between countries and can be analysed by game theory. We explore this using an acid rain example.

7.6.2 The acid rain game

This section uses a simple hypothetical two-country 'acid rain game' to illustrate the application of game theory to transboundary pollution problems. This problem introduces concepts from both co-operative and non-cooperative game theory. We start off by specifying the problem. There are two countries, the United Kingdom (subscript 1) and Sweden (subscript 2),

BOX 7.6 The Montreal Protocol

Chlorofluorocarbons (CFCs) have been implicated in depleting the stratospheric ozone shield since the 1970s. The depletion of the ozone layer is a truly global pollution problem in that all countries are likely to be affected, to some degree, by the health problems that the resulting elevated levels of ultraviolet light will cause. In September 1988, twenty-four countries signed the Montreal Protocol (Barrett, 2005: ch. 8) to restrict their production and consumption of CFCs to 50 per cent of 1986 levels by 30 June 1998. In London during July 1990, fifty-six countries agreed to further tighten restrictions on the use of these chemicals. This agreement involved the phasing out of halons and CFCs by the end of the twentieth century. An interesting aspect of this agreement is that a fund of $240 million was established to assist poorer countries to comply with this agreement. This amounts to a side payment to ensure that a negotiated settlement is achieved. The restrictions were further tightened at the fourth meeting in 1992 in Copenhagen, with a ban on CFC products brought forward to 1996, from 1999, and a ban on trade in these substances.

The agreements over the reduction in substances that damage the stratospheric ozone layer represents a relatively successful international environmental agreement, perhaps because the environmental costs were potentially large and shared by all countries and the costs, due to the development of new products, were declining through time. The use of side payments also facilitated the inclusion of poorer countries in the London agreement. This outcome contrasts with the current state of disagreement over the right course of action in relation to climate change (see Chapter 9). The stability of the Montreal Protocol is strengthened by the threat of trade sanctions if countries are found to be non-compliant or refuse to sign the protocol. This has been an effective deterrent against free-riding.

both of which generate sulphur dioxide from coal-burning. Emissions from the UK affect Sweden and vice versa. This is a reciprocal externality. Each country has a benefit-of-emissions function due to profits derived from burning coal (e.g. for electricity generation) and an external cost function due to damages caused by acid rain. These functions can also be given as abatement cost functions (which represent the emission benefit function) and an abatement benefit function. To make this example more concrete, we use the specific functional forms and parameter values in Table 7.4, but, if you prefer, look at the diagrams that come later.

The Nash equilibrium is where each country only takes account of its own external costs. The equilibrium (national) level of abatement for the UK is where

$$MAC_1(a_1) = MBA_1(a_1 \mid a_2);$$

that is, the marginal abatement cost $MAC_1(a_1)$ is equated with the marginal benefit of abatement in country 1, the UK, given the amount of abatement in (and thus the level of emissions from) country 2, Sweden, $MBA_1(a_1 \mid a_2)$. If the two countries agree to co-operate, then each country takes account of the other's benefits of abatement. Thus, for the UK:

$$MAC_1(a_1) = MBA_1(a_1 \mid a_2) + MBA_2(a_1 \mid a_2).$$

Using the numerical example given in Table 7.5, the results of a Nash strategy and a co-operative strategy are given in that table and Figure 7.5.

Table 7.5 gives the pay-off and the abatement level for all the combinations of strategies. Starting with the strategy in which both countries co-operate, this gives the highest overall abatement of 482.8 and the highest aggregate welfare of 38.8. However, without a binding co-operative agreement, both countries have an incentive to follow an unco-operative strategy—especially the UK, which is less affected by acid rain than Sweden.

Table 7.4 The acid rain game

Private costs and benefits	External costs and benefits
Private benefit of emissions:	External costs:
$B_i^e(e_i) = b_{0i}e_i - b_{1i}e_i^2$	$C_i^e(e) = c_i^e e^2$
$e_i^* = b_{0i}/2b_{1i}$	Total emissions:
where e_i^* is the private benefit-maximizing emission	$e = e_1 + e_2$
Abatement: $a_i = (e^* - e_i)$	$e^* = e_1^* + e_2^*$
Private abatement costs:	Aggregate abatement:
$C_i^a(a_i) = (B_i^e(e_i^*) - B_i^e(e_i^* - a_i))$ that is, the difference between maximum	$a = e^* - (e_1 + e_2)$
private benefits and benefits with abatement	Abatement benefit function:
	$B_i^a(a) = C_i^e(e^*) - C_i^e(e^* - a)$
Parameter values:	$c_1^e = 0.02$; $c_2^e = 0.05$
$b_{01} = 150$; $b_{02} = 150$;	
$b_{11} = 0.15$; $b_{12} = 0.15$	

For the co-operative solution to hold, there would have to be a side payment from Sweden to the UK to make the agreement stable. This is a concept from co-operative game theory, where it is necessary to ensure that players receive at least as much through co-operation as they do from not co-operating. In this example, a side-payment transfer to the UK means that Sweden gains sufficiently from co-operation to compensate the UK and still be better off. However, there may be a problem of countries 'pre-committing' to side payments in a believable way, which can harm prospects for co-operative agreements. However, promises of side payments can be used to entice countries into becoming part

Table 7.5 Transboundary pollution—the acid rain game

UK \ Sweden	Nash	Co-operate
Nash	Pay-off (£ millions)	Pay-off (£ millions)
	UK: 27.0	UK: 27.3
	S: 6.5	S: 6.3
	UK+S: 33.5	UK + S: 33.7
	Abatement (million tonnes SO_2):	Abatement (million tonnes SO_2):
	UK: 90.9	UK: 89.2
	S: 227.3	S: 241.4
	UK + S: 318.2	UK+S: 320.6
Co-operate	Pay-off (£ millions)	Pay-off (£ millions)
	UK: 22.3	UK: 23.4
	S: 15.9	S: 15.4
	UK + S: 38.2	UK + S: 38.8
	Abatement (million tonnes SO_2):	Abatement (million tonnes SO_2):
	UK: 241.4	UK: 241.4
	S: 189.7	S: 241.4
	UK + S: 431.1	UK + S: 482.8

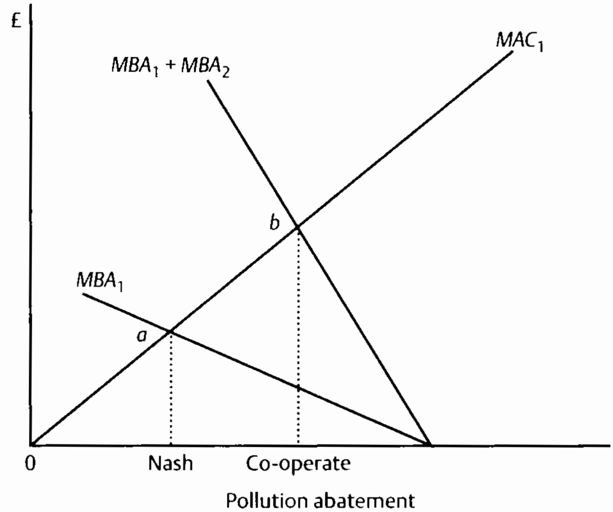

Figure 7.5 Transboundary pollution: the acid rain game

of international environmental agreements (IEAs) on transboundary pollution. Side payments were used during the negotiation process for the Montreal Protocol on the phasing out of CFCs. Side payments are also likely to be important in future global agreements on biodiversity conservation, and in greenhouse gas emission agreements.

Summary

In this chapter, we have introduced game theory as an approach to modelling the strategic interaction of a small number of economic agents. Situations in which small numbers of agents or coalitions of agents interact arise in environmental economics, where resources are shared. Environmental resources include global commons such as the atmosphere, regional air quality, and natural resources such as fisheries and grazing areas. The attributes of these problems are shared rights of ownership or poorly defined property rights, where agents compete to appropriate the benefits of a resource. Game theory enables us to analyse what the outcomes of these interactions might be.

An important game is the prisoner's dilemma, where the equilibrium is one where both players are worse off than they would be if they were to co-operate. Repeated games offer a new perspective on the problem, in that co-operation may actually emerge as an equilibrium, because—through time—players can punish defections by other players.

Co-operative game theory is about the formation and stability of coalitions between players. The approach can be viewed as complementary to competitive games, in that it considers only the best that players can achieve in different coalitions and abstracts from the mechanics of how a solution to a game is derived.

Game theory informs us how environmental conflicts and problems might be resolved, and it also goes some way towards explaining why problems have arisen in the first place—in particular, where individuals behave rationally, but counter to the common good.