Chapter 1

The Economy and the Environment: Two Parts of a Whole

1.1 Introduction

The purpose of this chapter is to describe the ways in which the economy and the natural environment are interlinked. To an extent, these interlinkages are all-embracing; every economic action can have some effect on the environment, and every environmental change can have an impact on the economy. By 'the economy', we refer to the population of economic agents, the institutions they form (which include firms and governments) and the interlinkages between agents and institutions, such as markets. By 'environment', we mean the biosphere, the 'thin skin on the earth's surface on which life exists', to quote from Nisbet (1991), the atmosphere, the geosphere (that part of the earth lying below the biosphere) and all flora and fauna. Our definition of the environment thus includes life forms, energy and material resources (see Chapter 8), the stratosphere (high atmosphere) and troposphere (low atmosphere). These constituent parts of the environment interact with each other: an example is the effect of changes in biosphere composition on the composition of the atmosphere. (The effect of biological entities on their physical surroundings forms the basis of the Gaia hypothesis: see Lovelock, 1987.) Such interactions will be important throughout this book. Even more important from our perspective are the effects of human activity on the environment, and the consequences of these affects on human well-being.

As an example, consider the generation of electricity. In extracting fossil fuels to use as an energy source, we deplete the stock of such fuels in the geosphere. In burning these fuels to release their energy, we also release carbon dioxide (CO_2) and sulphur dioxide (SO_2), both of which may

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As an example, consider the generation of electricity. In extracting fossil fuels to use as an energy source, we deplete the stock of such fuels in the geosphere. In burning these fuels to release their energy, we also release carbon dioxide (CO_2) and sulphur dioxide (SO_2), both of which may produce undesirable environmental impacts that reduce human (and therefore economic) well-being. These particular effects are considered in detail in Chapter 6. As another example, agricultural support policies may have environmentally damaging effects which in turn rebound on human welfare. Thus, subsidizing cereal production in the European Community (EC) led to higher prices for such cereals, which are important inputs to the livestock sector. Two effects amongst many may be remarked on; higher output prices encouraged farming practices which contributed to soil erosion in both the USA and UK (Heimlich, 1991), while livestock farmers' demand for cheaper substitutes for feed resulted in the loss of rainforest in Thailand, as producers sought to increase cassava production for export to EC livestock farmers.

1.2 Interlinkages between the economy and the environment

The interlinkages between the economy and the environment are summarized in Figure 1.1. Here we simplify the economy into two sectors; production and consumption. Exchanges of goods, services and factors of production take place between these two sectors. The environment is shown here in two ways: as the three interlinked circles E_1, E_2 and E_3, and the all-encompassing boundary labelled E_4. The production sector extracts energy resources (such as oil) and material resources (such as iron ore) from the environment. These are transformed into outputs; some useful (goods and services supplied to consumers) and some which are waste products, such as SO_2. There is some recycling of resources within the production sector, shown by the loop R_1, and within the consumption sector, as shown by the loop R_2.

The environment's first role, then, is as a *supplier of resources*. Its second is as a *sink*, or receptor, for waste products. These wastes may result directly from production, as already mentioned, or from consumption: when an individual puts out their garbage, or when they drive to work, they are contributing to this form of waste. In some cases, wastes are biologically and/or chemically processed by the environment. For example, organic emissions to an estuary from a distillery are broken down by natural processes – the action of micro-organisms – into their chemical component parts. Whether this results in a harmful affect on the estuary depends on a number of factors, including the volume of waste relative to the volume of receiving water, the temperature of the water and its rate of replacement. That is to say the estuary has a limited *assimilative* capacity for the waste. As the level of organic input increases, the process of breaking it down will use up more and more of the oxygen dissolved in water, reducing the ability of

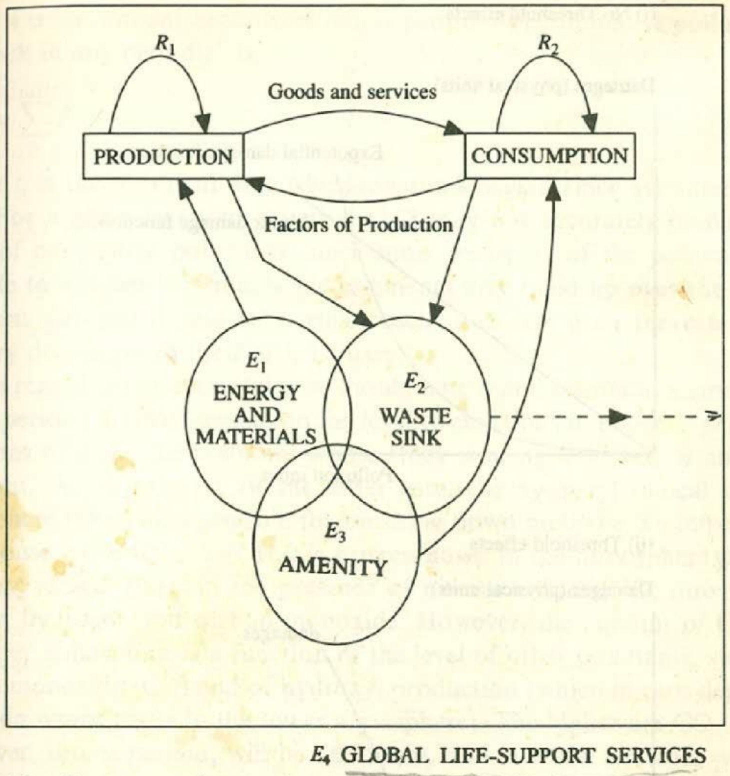

Figure 1.1 ***Economy–enviroment interactions***

the estuary to support fish. The notion of assimilative capacity has been criticised (see, for example, Nisbet, 1991), implying as it does that up to a fixed point emissions can occur with no deleterious impact. This is not strictly true in most cases, since what we have is a gradually increasing impact – although the rate of increase may exhibit abrupt changes due to 'threshold' effects. This is illustrated in Figure 1.2. However, the notion is useful in that it suggests that, up to a point, effects are not deemed important: only once the oxygen in the river drops below a critical level so that, for example, fish are no longer present, does the effect become 'significant' on some criteria.

For some inputs to the environment, there are no natural processes to transform them into harmless, or less harmful, substances. Such inputs, which are variously termed 'cumulative' and 'conservative' pollutants, include metals such as lead and cadmium, and man-made substances such as PCBs (polychlorinated biphenyls) and DDT (dichloro-diphenyl-trichloroethane). If, in our estuary example, PCBs are discharged into the water, then they will not be broken down by either chemical processes (oxidation) or through biological processes by micro-organisms (McLusky, 1989). Instead,

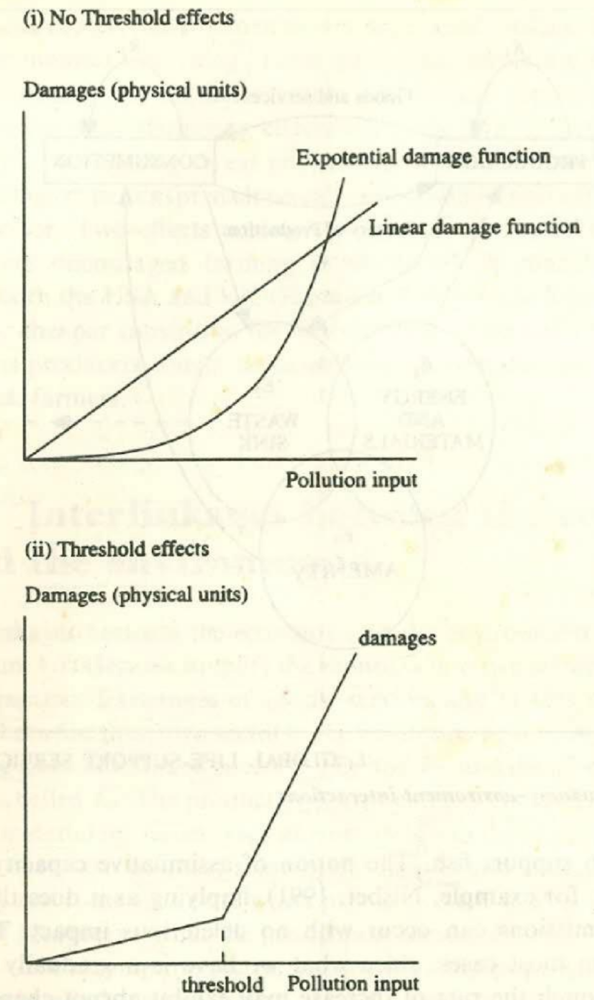

Figure 1.2 ***Possible damage functions***

they will build up either in the mud at the bottom of the estuary, or in fish or invertebrates. This latter process is known as 'bioaccumulation'. For conservative pollutants a positive flow in a year F_t adds to the stock S_t^c. This is not true for degradable, assimilative wastes, where the stock in any time period S_t^d depends on current flows *less* that amount removed by biodegradation, or by chemical reactions in the case of gases such as methane.

For degradable pollutants, such as organic effluents from brewing or paper production, and methane, the stock in any time period t is given by:

$$S_t^d = F_t - A_t \tag{1.1}$$

where A is the amount assimilated in any period. For cumulative pollutants, the stock in any period t^* is:

$$S_{t^*}^c = \sum_{t_i}^{t=t^*} F_t \tag{1.2}$$

(where t_i is the historical date when emissions began) since assimilation is zero. For a given location, equation (1.2) may not accurately predict the stock of cumulative pollutants, since some transport of the pollutants is possible to another location, while sediments may build up over the stock pollutant and put it 'out of harm's reach': this has been the case with mercury discharges to the Forth Estuary.

With regard to equation (1.1), we should note that the amount assimilated in any period (A_t) may depend on the level of emissions in previous periods: emissions of either the pollutant whose stock is being modelled or another pollutant. As an example of the latter case, the hydroxyl radical in the atmosphere (OH) is responsible for breaking down methane, an important greenhouse gas. Methane (CH_4) is broken down in the atmosphere by the hydroxyl radical (OH) in the presence of nitrous oxides (NO) into water vapour, hydrogen and carbon monoxide. However, the amount of OH in the upper atmosphere is a function of the level of other pollutants, such as carbon monoxide (CO) and of hydroxyl production (which in turn depends partly on ozone levels in the lower atmosphere). The higher are CO levels, the lower, *ceteris paribus*, will be OH levels, and thus the less CH_4 will be broken down.

Box 1.1 ***Uncertainty and the precautionary principle***

In many if not all cases of environmental management, there is some uncertainty over the effects of actions on the environment, and of the impact on humans of subsequent environmental changes. In some cases, the extent of this uncertainty is considerable. For example, while we know that carbon dioxide causes global warming, there is uncertainty as to the extent of warming caused by, say, a doubling of current CO_2 levels, and even more uncertainty about the physical effects this warming will have. Environmentalists will often argue that society should take action before such uncertainty is resolved, since the costs of not taking action may well be greater than the costs of preventative or anticipatory action taken now, especially when the absence of action today leads to irreversible undesirable environmental consequences (Taylor, 1991).

The policy stance of taking action before uncertainty about possible environmental damages is resolved has been referred to as the 'precautionary principle'. This was defined in the Declaration of the Third Ministerial Conference on the North Sea as: 'action to avoid potentially damaging impacts of substances that are persistent, toxic and liable to bioaccumulate even where there is no scientific evidence to prove a causal link between effects and emissions' (quoted in Haigh, 1993). Haigh (1993) argues that instances of the precautionary principle (PP hereafter) being applied include the Montreal Protocol on substances *likely* to damage the ozone layer, the North Sea conference decision to reduce polluting inputs to the North Sea by 50% by 1995 and the EC agreement to reduce CO_2 emissions. Indeed, the 1874 Alkali Act, often cited as one of the first pieces of environmental legislation in the UK, did not insist on *proof* that gases discharged from factories actually caused deleterious health effects, before they could be subject to control. More recently in the UK, the 1990 White Paper 'This Common Inheritance' states the PP as a first principle of environmental policy.

The PP, which can be extended to other areas of environmental management such as the conservation of fish stocks, would thus seem to be a widely accepted principle for wise environmental management. Indeed, it has also been argued to be an essential part of any sustainable development strategy, in the 1990 Bergen Declaration (signed by 84 countries as a follow-up to the Brundtland Commission report). However, two qualifications have emerged. First, the Rio summit adopted the PP to be applied by all countries, but only 'according to their capabilities', implying that the costs of actions under the PP should be considered, and might to deemed too great for some (poorer) countries. Second, the UK government, in the 1990 White Paper referred to above, stated that the PP should only be applied 'if the balance of likely costs and benefits justifies it' (paragraph 1.18). This second restriction is rather more severe, since to apply it would involve some estimates of the probabilities of different possible outcomes being known, that these outcomes could be physically described, and that they could be valued in monetary terms. But if this were so, then a more formal application of cost–benefit analysis could guide policy analysis: the PP would be incorporated in the treatment of risk (for example, by giving greater weight to the worst possible outcomes). Chapter 12 considers the treatment of risk and uncertainty in cost–benefit analysis in detail.

However, it should be noted that some have taken acceptance of the PP to mean that society should have as a firm objective the total elimination of activities where uncertain environmental damages are involved (Taylor, 1991). Examples of such bans do exist: for example, the banning of the disposal of radioactive wastes in the deep ocean, and the incineration of toxic wastes at sea. Alternatively, the PP could be taken to mean the minimisation of inputs of any effluents to any ecosystem. However, the economist might worry that the costs of either banning the disposal or minimising the input of effluents would be disproportionately large, and incur unnecessarily high opportunity costs for society. Such criticisms have been made by economists of, for example, expenditures on Environmental Protection Agency (EPA) mandated projects in the USA.

So far we have seen that the environment acts as a waste sink, as a partial recycling factory for human wastes from production or consumption and as

a source of energy and material resources. The next role to be considered is that marked E_3 in Figure 1.1. The environment acts as a supplier of amenity, educational and spiritual values to society. For example, people in Europe may derive pleasure from the existence of wilderness areas in Northern Canada or in tropical moist forests ('rainforests'), while native peoples living in these areas attach spiritual and cultural values to them, and the flora and fauna therein. We need to make precise the sense in which such values 'count' for economists. The theory of environmental valuation is set out in detail in Chapter 12. For present purposes, the question can be addressed by asking what constitutes economic value within the currently dominant economic paradigm, which is neoclassical economics. Neoclassical economics judges economic value as being dependent on social well-being, measured in a particular way. Social well-being is seen as depending on the (possibly weighted) sum of individuals' levels of well-being. Individual well-being is measured by utility, thus social welfare is the sum of individual utilities. There is thus no separate 'collective' good. The weighting of individual utilities is implicit in the social welfare function: see Johansson (1991) for a discussion. Individuals derive utility from consuming goods and services (meals, holidays) and from the state of the natural environment. This is because individuals use the natural environment to 'produce' goods/services and because they are made happier by the mere existence of environmental assets such as wilderness areas and blue whales. Environmental systems are also clearly essential for peoples' continued existence, but we discuss this later. A representative individual will have preferences which could be represented in the following generalised way:

$$U_A = U(X_1, X_2 \ldots X_n; Q_1, Q_2 \ldots Q_m) \tag{1.3}$$

Where U_A is utility, $(X_1 \ldots X_n)$ are goods and services produced in the production sector, and $(Q_1 \ldots Q_m)$ are environmental assets. Q_1 could be local air quality, Q_2 local water quality and Q_m the stock of blue whales. The environment thus supplies utility directly to individual A via the vector of assets, and indirectly via its roles in the production of the vector of goods and services $(X_1 \ldots X_n)$. Clearly one result of an increase in the output of any element of the X vector will be a decrease in the quantity or quality of an element in the Q vector. For example, suppose X_1 is consumption of services provided by owning a car, but car production and operation cause decreases in air quality, Q_1. An increase in the consumption of 'car services' increases utility ($\partial U_A/\partial X_1$ is positive), but this increase in car use decreases air quality ($\delta Q_1/\delta X_1 < 0$). This fall in air quality reduces utility in an amount $(\delta U^A/\delta Q_1 * \delta Q_1/\delta X_1)$. The net effect is thus ambiguous, depending on the relative strengths of these positive and negative changes.

What this simple example shows is that using the environment for one purpose (as a supplier of material resources) can reduce its ability to supply us with other services, such as the ability to breath clean air. This is why in Figure 1.1 the three circles E_1, E_2 and E_3 are shown as overlapping: there are conflicts in resource use. These conflicts would include the following:

- using a mountain region as a source of minerals means its amenity value is reduced;
- using a river as a waste-disposal unit means its amenity value is reduced and that we can no longer extract so many material resources (fish to eat) from it;
- felling a forest for its timber reduces the electricity-generating capacity of a dam, owing to soil erosion, and reduces amenity values since the forest's inhabitants (animal and human) are displaced or destroyed;
- preserving a wetland for its aesthetic qualities forgoes use of the drained land for agriculture.

The environment is thus a scarce resource, with many conflicting demands placed on it. We term the scarcity resulting from these conflicting demands *relative scarcity*, which in principle a correct set of (shadow) prices could solve. This we distinguish from *absolute scarcity*, whereby all demands on environmental services are simultaneously increasing (Daly, 1991). The major cause of absolute scarcity is economic growth: this implies an increasing demand for materials and energy, an increase in waste outputs (by the first law of thermodynamics, which is explained below) and increased demands for environmental quality as an input to recreational, educational and scientific activities. Yet if the amounts of environmental resources are fixed (limited assimilative capacity, limited supplies of minerals and so on) then absolute scarcity will increase as world economic growth occurs (but see Box 1.2).

It is apparent, therefore, that economics has a role to play, since much of economics is concerned with allocating source resources to conflicting demands. But it will also become clear that the *economic system*, primarily the market system, works very poorly in allocating environmental resources. The reasons for this failure are largely addressed in Chapter 2, but we can review the more important ones by saying that an imperfect specification of property rights results in a set of prices which send the wrong signals to producers, consumers and governments and that individual benefits of preserving our environment understate the collective benefits of preservation. Further, as Daly (1987) has argued, the price system may be unable to solve the problem of absolute scarcity, even with a correct set of relative prices in place. Such problems of 'scale' are only solvable, Daly believes, with quantity limits on resource use and on population.

Box 1.2 *Does rising output mean rising energy use?*

As economic growth occurs, energy and material demands per real dollar of output have tended to fall. For example, energy required per unit of real GDP in Denmark fell by 27% between 1979 and 1989 (World Resources Institute, 1992). In the UK, the ratio of primary energy use to GDP fell dramatically over the period 1950–90 (DTI, 1992). However, rising world population and an increased scale of economic activity would seem likely to produce a net increase in absolute scarcity over time. Moreover, recent work on energy saving and GDP growth by Robert Kaufman (1992) suggests that previous estimates of energy saving may be too high.

In Figure 1.3, energy use per unit of real GDP can be seen to have fallen for France, Germany, Japan and the UK over the last 40 years. This fall has traditionally been attributed to two factors: technological progress, which reduces the amounts of all inputs, energy inclusive, needed to produce one unit of output; and a real price effect, whereby rising real energy prices cause producers and consumers to substitute capital or labour for energy.

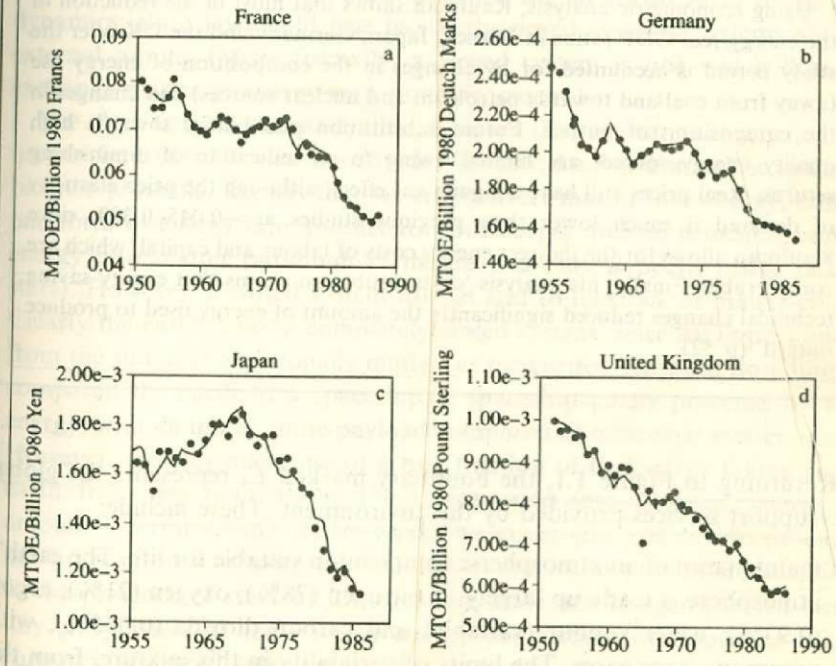

Figure 1.3 ***Energy use to GDP ratios in four countries***

Note: Actual value for the energy real/GDP ratio (circles) and the value predicted by Kaufman's regression model (solid line).

Source: R.K. Kaufman (1992) 'A biophysical analysis of energy/real GDP ratios', *Ecological Economics*, 6(1), 35–56.

Kaufman notes, however, that there are other reasons why the energy/real GNP ratio may fall. First is a change in the composition of energy use. Different forms of energy (oil, coal, nuclear) are aggregated by converting them into heat units (kilocalories). However, the amount of work per unit of heat equivalent is not constant across energy sources, with some energy sources (higher quality) being able to do more work per kilocalorie than others (lower quality). Thus, if over time there is a transition from lower to higher quality energy sources – say, from coal to natural gas – then the energy/GDP ratio will fall. Second, a change in the mix of final demand can also change energy use per unit of GDP if energy-intensive commodities are replaced by less energy-intensive ones (where energy intensity is measured as kilocalories per dollar of output).

Kaufman also argues that traditional measures of energy substitution due to real price effects overestimate energy savings, since they ignore the energy component of the capital and labour used instead of energy. Evidence on this point has been gathered by other authors: for example, Pimentel *et al.* (1973) calculated that, while the amount of direct energy used to produce a bushel of corn in the US fell 15% between 1959 and 1970, total energy use per bushel actually rose by 3% once the energy content of other inputs (tractors, pesticides) was accounted for.

Using econometric analysis, Kaufman shows that most of the reduction in the energy/real GDP ratios in France, Japan, Germany and the UK over the study period is accounted for by changes in the composition of energy use (away from coal and towards petroleum and nuclear sources) and changes in the composition of output. Future substitution possibilities towards high quality energy sources are limited owing to an indication of diminishing returns. Real prices still have a significant effect, although the price elasticity of demand is much lower than previous studies at −0.045–0.389, since Kaufman allows for the indirect energy costs of labour and capital, which are considerable. Finally, his analysis 'casts doubts on claims that energy-saving technical changes reduced significantly the amount of energy used to produce output' (p. 52).

Returning to Figure 1.1, the boundary marked E_4 represents the global life-support services provided by the environment. These include:

- maintenance of an atmospheric composition suitable for life. The earth's atmosphere is made up largely of nitrogen (78%); oxygen (21%); argon (0.93%); water vapour (variable) and carbon dioxide (0.035%), with numerous trace gases. The limits of variability in this mixture, from the point of view of continued existence, are small;
- maintenance of temperature and climate. The naturally-occurring greenhouse effect warms the earth from its 'effective' mean temperature of −18°C to the current global average of 15°C. Changes in the composition of the upper atmosphere can change this warming, as explained in Chapter 6.
- recycling of water and nutrients. Examples are the hydrological, carbon and oxygen cycles. Clearly, economic activity operates within this environment, and thus is shown as being encapsulated by it. The dashed line between E_2 and E_4 indicates that emissions can affect these global support services.

1.3 The first two laws of thermodynamics

Our last remaining task regarding Figure 1.1 is to ask whether the interlinkages portrayed are governed by any systematic physical processes or natural laws. We have already considered this to an extent in the discussion of assimilation. Now, however, we present two important physical laws, and discuss their relevance for the way we view the interrelationships shown. These laws are the first two laws of thermodynamics. Both laws hold true in strictly closed systems, systems with no external inputs. (More formally, a closed system is one which does not exchange matter or energy with its environment.)

The first law of thermodynamics states that matter, like energy, can neither be created nor be destroyed. This law, known also as the materials balance principle, implies that we can convert matter into energy, convert one form of energy into another form of energy and, in principle, convert energy into matter (although in nature this only happens inside nascent stars). However, a closed system cannot add to its stock of matter-energy. Clearly the earth is not a completely closed system, since we import energy from the sun, and occasionally matter, as meteorites. Kenneth Boulding has compared the earth to a spaceship: a spaceship partly powered by solar energy, with an initial, finite payload composed of terrestrial matter-energy. However, we only make use of a tiny fraction of the energy falling on the earth from the sun – about 1% is converted into chemical energy, an amount determined mainly by vegetative cover (the conversion process is known as photosynthesis, whereby carbon dioxide and water are combined, in the presence of sunlight, into carbohydrate and oxygen); whilst only a tiny proportion of total world energy production is accounted for by currently produced solar energy. The majority of world energy demand is met from the results of past solar energy, captured by photosynthesis and very gradually transformed into the fossil fuels: oil, natural gas and coal. Together, these three sources accounted for 94% of world energy production in 1991 (World Resources Institute, 1992).

However, the first law of thermodynamics has two important implications in addition to limits on matter-energy supply. The first is that, as more matter is extracted by the production process, more waste is generated which must eventually be returned to the environment, since the matter-energy content of the extracted material cannot be destroyed. Thus, if economic growth brings an increase in iron and aluminum extraction to satisfy increased demand, more iron ore waste, bauxite processing waste and scrap metal will eventually be returned to the environment. Economic growth which results in increased extraction of material and energy resources must produce an equivalent increase in residuals output. In this sense, 'consumption' is a rather inadequate description of what consumers do.

Secondly, the first law places limits on the degree to which resources can be substituted for each other in production. The degree of substitutability between inputs derived from the environment, man-made capital and human capital is a very important parameter in discussing 'limits to growth'. Christensen (1989) has argued that the first law places definite upper limits on this substitutability, and that neoclassical economics has ignored this fact because it has ignored the physical features of production. Christensen views the neoclassical notion of land, labor and capital as the primary inputs to production as a poor reflection of reality. He prefers to count all material and energy resources not produced by the economic system as primary factors. These primary factors are then combined with man-made capital and human capital to produce outputs, in endogenously determined structures (firms and markets). Output can only be increased by varying *all* of these inputs, or at least more than one at a time. From this perspective, the marginal products of neoclassical economics do not exist, being replaced by some sort of joint marginal products. Because man-made capital must be combined *with* primary inputs, the degree of substitutability between the two is very limited; that, is the elasticity of substitution is close to zero. We take this issue up again later on.

The second law of thermodynamics is also known as the entropy law, and will be familiar to many. There are a great many ways of stating this law, but for our purposes the following is useful: 'In a closed system, the use of matter-energy causes a one-way flow from low entropy resources to high entropy resources; from order to disorder. As an energy resource, for example, is used, the amount of work that energy can do is diminished.' The entropy law can also be stated as 'no process is possible where the sole result is the transfer of energy from a cooler to a hotter body' (Khalil, 1990). The alternative suggests what happens to energy when it is used. Consider a piece of coal. When the coal is burnt, the energy in it is released. We know from the first law that energy cannot be destroyed. We may be able to recapture some of the energy in a heat-exchanger, for this

is where the energy 'goes': it dissipates as heat. This is due to the tendency towards equilibrium in thermodynamic systems, and thus a tendency for temperature differences, in our example, to be equalised. The major implication of the second law is that energy cannot be recycled in such a way that we get back *all* the capacity of the original energy source to do useful work, since the act of using the original low-entropy resource will result in some of its energy being lost as heat. If the earth is a closed system, with a limited stock of low entropy energy resources (fossil fuels), then that system is unsustainable, since economic activity inevitably degrades the energy resource so that, eventually, no capacity for useful work could remain.

The entropy law has an important implication for the recycling of matter, since production and consumption of matter can lead to its dissipation, and scarce matter or energy must be used up to recycle it. Biological and ecological systems are also constrained by the entropy law, particularly in terms of the proportion of energy which is passed between trophic layers. The earth is not, however, a closed system: we obtain energy directly from the sun, which we have a limited capacity to utilise. Thus, whilst the entropy law is very useful in understanding the limits of matter and energy recycling, it is not necessarily the harbinger of doom it once appeared to writers such as Georgescu-Roegen. Some economists (for example, Khalil, 1990) have disputed its applicability to the economic system (but see the reply by Lozada, 1991), whilst others have pointed to the possibility of technological progress offsetting the entropy process for material resources. Finally, we note that it seems more likely that the first law of thermodynamics, with its implications of increased residuals output, will be more likely to set a limit to growth (given the earth's limited capacity to assimilate these residuals) before the entropy constraint becomes binding and the world runs out of useful energy.

1.4 Conclusions

The economy and the natural environment are linked to each other in four ways, with the environment supplying material and energy resource inputs, waste assimilative capacity, amenity, educational and spiritual values, and global life support services to the economic process. These interlinkages are dynamic, in that they are continually changing. The first and second laws of thermodynamics partially govern the interrelationships, although economists disagree on how important the two laws are in terms of their implications for future economic activity.

Technical note: game theory

For many problems in environmental economics, game theory provides a useful tool. Game theory is concerned with the strategic actions of different agents (firms, consumers, governments and so on), where these actions are in some way interlinked. For example, the interaction between firms in a permit market, or arguments between countries over cuts in carbon dioxide emissions can be represented as games. This note gives a brief review of those parts of game theory used in this book, in Chapters 6 and 10. Gibbons (1992), and Fudenberg and Tirole (1991) provide an excellent introduction to the field. We use Gibbons' notation in what follows.

Assume there are $i = 1 \ldots n$ agents who each can choose different strategies s_i from their sets of all possible strategies S_i : thus player 1 may choose s_1^* or s_1 from their strategy set S_1. Depending on their choice of strategy, and the choices of the other players, agents will receive payoffs of u_i, where $u_i = f(s_1 s_2, \ldots s_i \ldots s_n)$ so that u_i depends on the strategies chosen by all players. Games are usually categorised according to whether players all make their decisions simultaneously (static games) or sequentially (dynamic games); whether players know all the pay-off functions $u_i(\cdot)$ for all players or not (games of complete and incomplete information); and whether games are once-off or repeated. This note restricts itself to explaining three other pieces of terminology: dominated strategies, Nash equilibrium and leader–follower games.

To illustrate dominated strategies and Nash equilibrium, consider the following situation. Two countries (A and B) are bargaining over whether to cut sulphur dioxide emissions. Each country can make one of two decisions: to cut its emissions by a certain amount, or to make no cut. Because sulphur dioxide is a transboundary pollutant, A is affected by B's emissions, and vice versa. Each country knows what the pay-offs of each strategy will be, depending on what the other country does (so that this is a game of complete information). Think of these pay-offs as dependent on control costs net of avoided damages. Each country decides simultaneously what action to undertake. The game ('game 1') is set out below:

Game 1 ***Pay-offs and strategies for emission reductions***

		Country B's actions	
		cut	not cut
Country A's actions	cut	(50, 50)	(−40, 60)
	not cut	(60, −40)	(−30, −30)

The pairs of numbers in parentheses indicate the pay-offs for each combination of actions, with A's pay-offs given first in each case. Negative numbers represent net losses to either country. Thus if A decides not to cut emissions, but B decides to cut, then A incurs no control costs and gets some benefits due to reductions in emissons originating from B: its pay-off is +60. But B will lose in net terms, since it does all the abatement, and receives no benefits from reduced deposition from A. B's payoff in this case is −40. Clearly the best outcome or most efficient solution from a social point of view is {cut, cut}, but how likely is this to occur? In this case, not likely at all. To see this, consider A's choices. If B cuts, the most profitable action for A is not to cut, since 60 is greater than 50. If B does not cut, A's best option is again not to cut, since a loss of 30 is less undesirable than a loss of 40. So no matter what B does, A will choose not to cut: we can say that the strategy 'not cut' strictly dominates the strategy 'cut'. Applying similar reasoning to B's decision, 'not cut' again strictly dominates 'cut'. Rational players should not play strictly dominated strategies, so the outcome of this one-shot game will be {not cut, not cut}, which is socially inefficient.

This game is an example of the 'prisoners' dilemma' type of game, where co-operation would yield an outcome preferred by both parties if they were able to negotiate before the start of the game and obtain binding commitments, but where simultaneously taken utility-maximising decisions yield worse outcomes than the co-operative solution. (Although, as Gibbons shows (p. 97), in an infinitely repeated 'prisoners' dilemma', co-operation may result: (the Folk theorem.)) Not all static, two-by-two games are prisonners' dilemmas. For example, in game 2, where the pay-offs have been slightly changed , the strategy 'cut' strictly dominates the strategy 'not cut' for both A and B, so here selfish behaviour will lead to the socially efficient outcome.

Game 2 ***Alternative pay-offs for emission reductions***

		Country B's actions	
		cut	not cut
Country A's actions	cut	(70, 50)	(−20, 40)
	not cut	(60, −20)	(−30, −30)

Sometimes, however, games cannot be solved by this method, which is known as 'the elimination of strictly dominated strategies'. A different approach to solving for the outcome of such simple, static games is therefore necessary. The most widely used is that of deriving the Nash equilibrium for a game. Nash equilibrium as a concept is closely related to the elimination of strictly dominated strategies, but is a stronger notion of the solution to a game, in that it is more likely to produce a solution. By this we mean that any strategy choice that survives the elimination of dominated strategies is a Nash equilibrium, but that the reverse is not true. In fact, Nash's theorem states that in any finite game (that is, where the number of players and the number of possible strategies is less than infinite) at least one Nash equilibrium will exist. Note, however, that it may not be the only one, meaning that we must try to identify which is the 'best' of these equilibria in order to solve the game this way. A Nash equilibrium is informally defined as follows: if all players choose strategies that, for each player, correspond to their best action given the best actions of all other players, then that set of best strategies is a Nash equilibrium. At the Nash equilibrium, no player wants to change his predicted action, since that action is the best she can do given what everyone else has done.

Finding the Nash equilibrium of a game can be accomplished in a variety of ways. For game 1 above, one way is to start with player B, and find their best response to each action that A could take; then find the best response of A to each action B could take. Thus, in our example, B would say, 'Well, if A goes cut, I should not cut; but if A does not cut, then neither should I.' So, irrespective of A's decision, B will want not to cut. A would say, 'Well, if B goes cut, I would want not to cut; and if B does not cut, then neither will I ($-30 > -40$).' So the Nash equilibrium is {not cut, not cut}.

In fact, any strategy combination that is a Nash equilibrium will survive the elimination of strictly dominated strategies. But in the game below, we show that, while a Nash equilibrium exists, no solution can be found by the elimination of strictly dominated strategies. This game (game 3) shows the pay-offs to two pressure groups (the National Farmers Union and Friends of the Earth) when three strategies are available to them: support policy X, support policy Y, and oppose both X and Y by supporting neither. Here, the pay-offs are the utility the NFU and FOE get depending on which policy reform they support and the actions of their lobbying opponents.

Game 3 ***Lobbying over policies***

		NFU action		
		Policy X	Policy Y	Neither
FOE action	Policy X	(0, 8)	(8, 0)	(10, 6)
	Policy Y	(8, 0)	(0, 8)	(10, 6)
	Neither	(6, 10)	(6, 10)	(12, 12)

The Nash equilibrium is found as follows. Take FOE first. If the NFU support policy X, then FOE would want to support Y; if the NFU supports Y, FOE will want to support X, and if the NFU supports neither, then FOE will do the same. In the solution below these best actions for FOE are

marked with a star; the same is done for the NFU. The cell with two stars is the Nash equilibrium and the (unique) solution to this game. But this solution could not be found by the elimination of strictly dominated strategies, since no strictly dominated strategies exist in this game. For example, FOE would choose X if the NFU choose Y; but would choose Y if the NFU chose X; and would choose neither if that was also the choice of the NFU. The outcome (12,12) or {neither, neither} is the unique Nash equilibrium in this case. However, as mentioned above, some games have more than one Nash equilibrium. For example, in game 4 where we return to pay-offs to two countries from emission reductions, both {cut, cut} and {not cut, not cut} are Nash equilibria. Obviously, each country would rather reach the former outcome, but this will only occur if country A can assure itself that country B will cut emissions if A also cuts. In this case, A can be sure of this (with complete information), since the outcome {cut, cut} is in a sense 'assured', since if A does decide to cut, B's best pay-off is to cut also. This is an example of an assurance game (Sandler, 1992). Gibbons gives an example of the derivation of a Nash equilibrium in a static problem of Garrett's 'Tragedy of the Commons': you will find this set out in Chapter 9.

Game 3 ***Solution***

		NFU action		
		Policy X	Policy Y	Neither
FOE action	Policy X	(0, 8*)	(8*, 0)	(10, 6)
	Policy Y	(8*, 0)	(0, 8*)	(10, 6)
	Neither	(6, 0)	(6, 10)	(12*, 12*)

Game 4 ***An assurance game of emission reductions***

		Country B's actions	
		cut	not cut
Country A's actions	cut	(80, 80)	(−120, 0)
	not cut	(0, −120)	(0, 0)

☐ *Sequential games*

Leader–follower games are an example of a sequential game, since not all parties make their moves at the same time. An example of such a game in the environmental economics literature is Hoel's paper (1989) on unilateral cuts in emissions of a global pollutant by one country. For example, if Norway goes ahead with a dramatic cut in its emissions of greenhouse gases, will other countries follow suit, or will they free ride? The best known economic example of such games is Stackleberg's (1934) model of a duopoly, where one firm (the leader) makes an output (or pricing) decision: the other firm observes this decision, and then makes its own. Here we run through the basic idea of a dynamic game, and then analyse Hoel's paper.

Sequential games have as their key feature that not all players make their moves simultaneously, and they may be solved through the process of 'backwards induction'. The simplest of these games involve situations where all stages of the game are known to all players (perfect information), who also know each others' pay-off functions (complete information). Backwards induction works as follows. Consider the following two-stage game. First, a monopoly union sets a wage w. Next, a firm decides how many workers to employ at this wage. The pay-off to the firm (its profits) depend on revenues (R), which in turn depend on the number of workers it hires (L); and on its wage bill, wL. The firm maximises profits subject to the wage demand of the union; the solution to this problem gives a 'reaction curve' $L^*(w)$, where L^* is the best level of L for any level of w. But the union can solve this problem too. It thus makes a decision about what wage to claim in period 1 by maximising its pay-off function u, where $u = u(w, L^*(w))$. Thus the strategy choice in the first period depends on the choice in the second period: this is backwards induction. It is possible to find Nash equilibria in dynamic games by this method: these equilibria are termed 'sub-game perfect' if they imply Nash equilibria at each stage of the game (that is, at each 'play'). This in turn implies, as Gibbons shows, an absence of unbelievable threats or promises from any player at any stage.

Hoel first considers a static game similar to the example at the beginning of this note. Two countries are affected by a global pollutant. In each country, the benefits of pollution control are $B_i = B_i(X1 + X2)$, where $X1$ and $X2$ represent emission reductions in countries 1 and 2; and the costs of pollution control are $C_i = C_i(X_i)$. Note that for country i, its benefits depend on emission reductions by both countries (since the pollutant is a global one), but that its control costs depend only on its own level of emissions reduction. We assume that, with respect to X_i, the first derivatives of $B_i(\cdot)$ are positive, but the second derivatives negative (that is, $B' > 0$ but $B'' < 0$) and that $C', C'' > 0$ (that is, marginal control costs are increasing). In a static game with no co-operation, each country solves the problem:

$$MAX: B_1(X1 + X2) - C_1(X1)$$

which gives as a necessary condition:

$$B'_1(X1 + X2) = C'_1(X1)$$

This gives the best choice of emission reductions from country 1 as a function of country 2's emission reduction: a reaction function, which we can call $R_1\ (X2)$. Similarly, $R_2\ (X1)$ would give country 2's best response to any level of $X1$. These functions are shown below in Figure T.1. Taking country one, it may be seen that its optimal level of emission reduction falls as $X2$ increases, since it benefits from these reductions by country 2, and since marginal benefits are decreasing whilst its own marginal control costs are increasing. The point where the two reaction functions cross (v, in Figure T.1) is in fact a (static) Nash equilibrium, since it shows a coincidence of best moves by each party. If the two reaction funtions do not cross (for example, if they are parallel to each other), then there will be no Nash equilibrium in this game, whilst non-linear reaction functions admit the possibility of multiple Nash equilibria.

But what if country 1 (Norway, say) acts unselfishly? Hoel shows the outcome by including an extra term in country 1's net benefit (pay-off) function, namely $h(\cdot)$. It becomes:

$$\Pi = B_1(X1 + X2) - C_1(X1) + h(X1 + X2)\ldots h > 0$$

Here, $h(\cdot)$ shows the additional benefit gained by country 1, which can be thought of as an altruistic benefit. If country 1's net benefit is now maximised, and a new reaction function ($R\#_1\ (X2)$) derived, it will lie to the right of $R_1\ (X2)$ and the new Nash equilibrium will change to v'.

This unselfishness can also be modelled as a sequential, leader–follower game. Let country 1 be the leader and country 2 the follower in the next period. The solution to the Stackleberg game can be found by backwards induction: finding country 2's optimum response to country 1's move. Hoel shows that this will involve country 1's optimal emissions being lower, the higher is h, with country 2's emissions rising, the greater the reduction by country 1. He also shows that total emissions will fall. Figure T.2 shows this

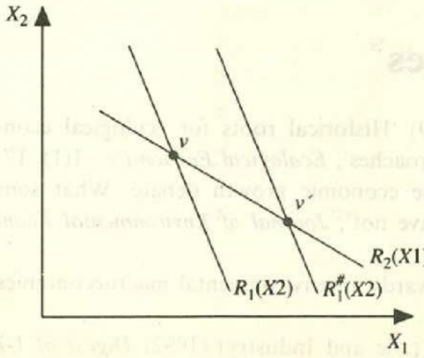

Figure T.1 ***Nash equilibrium***

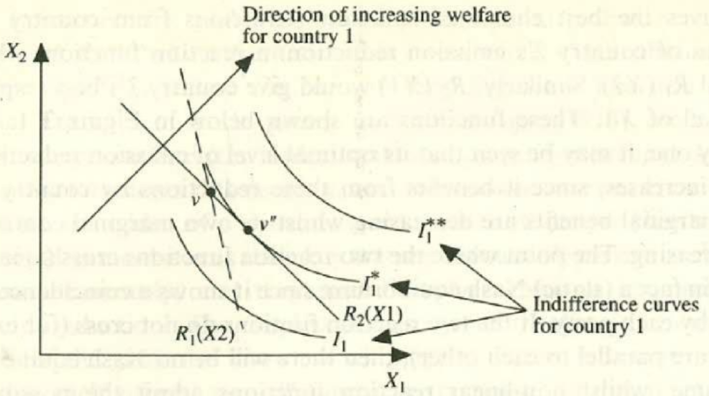

Figure T.2 ***Stackleberg equilibrium***

result for $X1$ and $X2$ graphically. The response function of country 2 is again R_2 ($X1$): remember that country 2 acts selfishly. Also shown are indifference curves for country 1. Along each indifference curve (I_1), net benefits for country 1 are constant. Country 1 can anticipate country 2's response to any level of $X1$, since this is given by R_2 ($X1$). Country 1 wants to maximise its net benefits subject to this best response by country 2; this is the same as saying that country 1 wants to be on the highest indifference curve which is just tangent to country 2's response curve, which is at point v''. This has country 1 making higher emissions cuts (and country 2 making lower emissions cuts) than the original simultaneous move Nash equilibrium at v, where both countries behave selfishly.

Hoel goes on to show that circumstances can exist whereby unilateral, unselfish action can actually increase total emissions, but we leave the reader to study Hoel's paper to investigate this result.

References

Christensen, P.P. (1989) 'Historical roots for ecological economics – biophysical versus allocative approaches', *Ecological Economics*, 1(1), 17–37.

Daly, H.E. (1987) 'The economic growth debate. What some economists have learned but many have not', *Journal of Environmental Economics and Management*, 14(4), 323–337.

Daly, H.E. (1991) 'Towards an environmental macroeconomics', *Land Economics*, 67, 255–9.

DTI (Department of Trade and Industry) (1992) *Digest of UK Energy Statistics*, London: HMSO.

Fudenberg, D. and J. Tirole T (1991) *Game Theory*, Cambridge, MA: MIT Press.

Gibbons, R. (1992) *A Primer in Game Theory*, New York: Harvester Wheatsheaf.

Haigh, N. (1993) 'The precautionary principle in British environmental policy', mimeo, London: Institute of Environmental Policy.

Heimlich, R.E. (1991) 'Soil erosion and conservation policies in the United States', in N. Hanley (ed.), *Farming and Countryside, an economic analysis of external costs and benefits*, Oxford: CAB International.

Hoel, M. (1989) 'Global environmental problems: the effects of unilateral actions taken by one country', discussion paper 89/11, Department of Economics, University of Oslo.

Johansson, P.O. (1991) *An Introduction to Modern Welfare Economics*, Cambridge: Cambridge University Press.

Lovelock, J. (1987) *Gaia: A New Look at Life on Earth*, New York: Oxford University Press.

Kaufman, R.K. (1992) 'A biological analysis of energy/real GDP ratio: implications for substitution and technical change', *Ecological Economics*, 6(1), 35–57.

Khalil, E.L. (1990) 'Entropy law and exhaustion of natural resources : is Nicholas Georgescu-Roegen's paradigm defensible?', *Ecological Economics*, 2(2), 163–179.

Lozada, G.A. (1991) 'A defence of Nicholas Georgescu-Roegen's paradigm'. *Ecological Economics*, 3(2), 157–61.

McLusky, D. (1989) *The Estuarine Ecosystem*, Glasgow: Blackie.

Pimental, D., L. Hurd, A. Belotti, M. Foster, I. Okra, O. Scholes and R. Whitman (1973) 'Food production and the world energy crisis', *Science*, 182, 443–9.

Nisbet, E.G. (1991) *Leaving Eden – To protect and manage the earth*, Cambridge: Cambridge University Press.

Sandler, T. (1992) 'After the cold war: secure the global commons', *Challenge*, July–August, 16–23.

Taylor, R.E. (1991) 'The precautionary principle and the prevention of pollution'. *Ecos*, 12(4), 41–45.

World Resources Institute (1992) *A Guide to the Global Environment*, Oxford: Oxford University Press.