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Economic Analysis of Sustainable Growth and Sustainable Development

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ABSTRACT

This paper attempts to analyze sustainability concepts, such as sustainable growth, sustainable development and sustainable resource use, in terms of the conventional neoclassical theory of economics. It then tries to analyze why free market forces may not achieve sustainability, and how policy intervention may help or hinder sustainability.

Several different definitions of sustainability are reviewed. Most require that the "quality of life" should not decline over the long-term future. Many can also be interpreted in terms of maintaining an economy's capital stock. However, a relevant definition of capital stock still has to be chosen, and this means judging how significant, essential or substitutable are the various natural and man-made resource inputs to the economy's production processes.

A number of simple models of the economy and the environment are used to explore these issues. One model uses comparative static analysis to explain why different tradeoffs may be made between consumption and environmental quality at different stages of economic growth. Other models use optimal control theory to examine sustainability over time in the context of both non-renewable and renewable resources. Such models may not achieve much realism, but they should help to clarify conceptual thinking about sustainable development.

The main results suggested by these simple models are that, if non-renewable resource inputs are essential, then inadequate technical progress and open access to environmental resources may be the key factors that cause unsustainability. Government intervention, in the form of resource conservation subsidies or depletion taxes, is shown both to correct the open access problem and to improve sustainability. Conversely, government subsidies for resource depletion aimed at encouraging development will harm sustainability. But improving sustainability by slowing down resource depletion also may mean lower initial levels of consumption and utility.

The suggested implications for policy are that conventional environmental policies may also improve sustainability, making a separate sustainability criterion redundant in practice; and that politically difficult short-term sacrifices may be needed to reach optimal and sustainable growth paths. "Conventional environmental policies" need not always mean making the polluter pay for externalities. More important is that property rights over the environment are first defined and enforced, if this is possible.

A simple model in which renewable resource inputs are essential shows how population growth can threaten sustainability, and how poverty and environmental degradation can be linked, establishing the case for development assistance. The role of a more equal income distribution as part of sustainable development is briefly discussed. Giving environmental property rights to the poor may both reduce poverty and improve the

environment. This is true whether the poor are the polluters (by being so poor that they degrade their own land and cause floods, siltation, etc., elsewhere), or the pollutees (by suffering air and water pollution in cities).

If improved environmental policy alone is not enough to achieve sustainability, so that a separate explicit sustainability policy is necessary, one must ask how it can be applied at both the system and project level. At the system level it is fairly clear, at least in theory: aggregate constraints (either economic or regulatory) must be imposed to control the depletion of whatever resources have been determined to be important for sustainability. Such constraints should drive up the price of such resources to whatever level is necessary to induce the required conservation efforts throughout the system. Such efforts are equivalent to intergenerational compensation investments. An example of this kind of process is already under way with international agreements to reduce the use of CFCs.

Making sustainability operational at the project level is much harder, even conceptually. System sustainability cannot be disaggregated into project rules in the simple way that system optimality can be disaggregated into cost-benefit rules for project appraisal. Many writers suggest that sustainability will be assured, if "intergenerational compensation" projects are required for any group of projects that has a harmful overall effect on environmental resources. This is an attractive and fairly operational concept, but it is not clear how groups of projects should be defined, how compensation should be paid, and who should pay it, particularly in the private sector.

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SUMMARY

The paper attempts to analyse sustainability concepts, such as sustainable growth, sustainable development and sustainable resource use, in terms of conventional neoclassical economic theory. It then tries to analyse why free market forces may not achieve sustainability, and how policy intervention may help or hinder sustainability. Many of the concepts and ideas appear in "Environment, Growth and Development" (World Bank Development Committee Pamphlet 14). [Section 1]

We set out a general model depicting stocks and flows of economic and environmental variables such as capital, labour and natural resources (hereafter abbreviated to just "resources"). Each variable consists of many different categories, and weights such as prices or natural resource accounting values are needed to calculate aggregate stocks and flows of variables. General interdependencies are pointed out, such as the effect of resource and pollution stocks on output ("environmental productivity") and on welfare ("environmental amenity"). Criticisms of neoclassical assumptions inherent in the model are discussed. [Section 2]

Dozens of different verbal definitions of sustainability concepts are listed in an appendix. The general economy/environment model is used to suggest quantified, sometimes conflicting interpretations of these definitions. Key points which emerge are:

- (1) The geographical and temporal context for sustainability concepts must always be made clear;
- (2) "Growth" generally ignores the direct effect that the environment may have on social welfare, whereas "development" takes it into account.
- (3) The most common, although subjective, definition of "sustainability", is that the welfare of future generations should not be less than the welfare of the current generation, i.e. utility should be non-declining.
- (4) "Sustainable resource use" focuses on maintaining a stock of renewable resources. Looking objectively at the resource base may be more relevant than notions of intergenerational welfare, when studying poor developing country economies.
- (5) Many definitions of "sustainable development" explicitly require attention to the needs of the current poor as well as to the needs of the future.

Many different definitions of sustainability can be interpreted in terms of maintaining the economy's capital stock. However, capital stock can also be defined in several different ways, so a choice of definition is still necessary. The relevant choice requires a judgement of how significant, essential or substitutable are the various natural and man-made resource inputs into the economy. [Section 3 / Appendix 1]

The uses and shortcomings of abstract optimal growth models for analysing sustainable development are discussed. Optimal growth models can never achieve much realism, but may be useful for clarifying concepts and for making general suggestions for policy in what is a very diverse and complex field. Sustainability may be viewed as a constraint on the conventional optimality criterion of maximising discounted utility, rather than as a replacement for it. Providing an ethical foundation for a sustainability constraint requires

that people are seen as having separate preferences for private and social choices. In practice governments may be no more concerned about sustainability than individuals. [Section 4]

Comparative static analysis is used to analyse rational tradeoffs between consumption and environmental quality at different stages of economic growth. Resource inputs are ignored, and a given output is assumed to be divided between consumption and pollution control expenditure. It is possible to view a commonly observed pattern, that environmental quality first declines and then recovers as industrialisation proceeds, as an optimal allocation of resources. One can then perhaps conclude that continued environmental improvement is generally compatible with economic growth in the mature stages of development. However, it is also possible that environmental policy is inevitably weak during early industrialisation, and that truly optimal consumption-environment tradeoffs actually lead to continually declining environmental quality as growth proceeds. [Section 5]

Optimal control theory is applied to radical simplifications of the general economy/environment model, in order to examine sustainability in the context of non-renewable and renewable resources. Mathematical details are given in corresponding appendices. The first model is of "cake-eating", with exogenous technical progress in the transformation of a single non-renewable resource into a consumption good. The optimal path shows steady growth of consumption (i.e. sustainability) only if the rate of technical progress exceeds the rate at which future utility is discounted; so people's concern for the future does affect sustainability. [Section 6 / Appendix 2]

The second model is also of cake-eating, but here an individual's utility depends not only on the rate at which he depletes his own resource stock, but also on the total resource stock owned by all individuals. This total resource effect is either direct (environmental amenity) or via the production function (environmental productivity). In either case, non-cooperative (privately optimal) resource depletion results in a "tragedy of the commons": private rates of resource depletion are greater than is socially optimal, and the economy is less sustainable.

Government intervention in the form of resource conservation subsidies or depletion taxes is shown both to correct the tragedy of the commons and to improve sustainability. Conversely, government subsidies for resource depletion, as often occur in reality, have the opposite effect. However, slowing down resource depletion also means lower initial levels of consumption and utility. The suggested (not proved) implications for policy are that conventional environmental policy may also improve sustainability, making a separate sustainability criterion redundant in practice; and that politically difficult short-term sacrifices may be needed to reach optimal and sustainable growth paths. "Conventional environmental policy" need not always mean making the polluter pay for externalities; more important is that property rights over the environment are first defined and enforced. [Section 7 / Appendix 3]

The third model looks at steady states of an economy which also uses accumulated capital as well as resource flows to produce output (via a Cobb-Douglas production function). Environmental amenity or environmental productivity, combined with privately optimal resource depletion, again

results in socially excessive resource depletion rates and lowered sustainability. A government conservation incentive again slows resource depletion. It also raises the rate of return on capital (the interest rate), because the resource price is driven up and capital investment results in resource savings. Possible limits, imposed by the laws of thermodynamics, on capital substitution for resources (limits which the Cobb-Douglas formula does not recognise) and on technological progress are briefly discussed. Such limits, combined with the finiteness of global resources of materials and energy, may ultimately constrain economic growth. [Section 8 / Appendix 4]

The fourth simple model is based on a single renewable resource ("corn"), where there is exogenous population growth, no technical progress in corn-growing and harvesting, no environmental externalities, and a minimum consumption level needed for survival. This is clearly more relevant to developing countries whose economies depend largely on renewable resources. The optimal solution can be one of sustained growth of consumption and welfare, but only if two conditions both hold. The first is that the resource growth rate exceeds the sum of the utility discount and population growth rates; if not, grinding along forever at subsistence consumption is optimal. The second condition is that the initial resource growth is large enough to feed the initial population; if not, people are forced to eat resource capital (seedcorn) simply to survive, and total depletion and catastrophe are the inevitable result. This model provides a rationale for common development policies such as agricultural improvement, population control and the need for outside assistance. Possible extensions to include capital accumulation, non-renewable resources and environmental externalities are suggested. [Section 9 / Appendix 5]

We then discuss the roles of a more equal income distribution, and/or of meeting basic needs, in sustainable development. To some extent these may be separate issues, requiring separate redistribution policies. However, the corn-eating model showed how poverty and environmental degradation can be linked. Also, the allocation of environmental property rights to the poor may both alleviate poverty and improve the environment if there are both rich and poor classes in society. This is true whether the poor are the polluters (by being so poor that they degrade their own land and cause floods, siltation, etc elsewhere), or the pollutees (by suffering air and water pollution in cities). [Section 10]

Observable interest rates, as distinct from unobservable utility discount rates, clearly affect sustainability, since they determine the relative weight given to present and future costs and benefits in discounting procedures used to make investment decisions. We examine the case that real interest rates are "too high" by looking at the interest rate as the balance of demand and supply for investment funds. On the demand side, it is argued that environmental policy may lower demand and thus reduce the economy's interest rate. This depends on assumptions that (1) "resource-using" investments are much commoner than "resource-saving" investments; (2) resource use results on balance in harmful externalities. Using environmental policy to internalise these externalities therefore drives up resource prices, shifts investment towards resource saving, and reduces total investment demand. On the supply side, there is a purely moral case that people ought to care more for the future and lower their utility discount rate. There is also an economic case:

investment supply will be too low (and interest rates too high) if people are unaware of the ultimate limits to growth, and hence have excessive expectations of consumption growth rates in the distant future. [Section 11]

The importance of imperfect information is recognised but not analysed; people may be depleting resources unsustainably without knowing it. Uncertainty about the future is also important, and the possibility of environmental catastrophes may justify greater environmental protection as a form of insurance. [Section 12]

Finally, we look at how a sustainability criterion (if it is accepted as a social goal) may be made operational. First of all one must be clear about what system level (species, ecosystem, nation or planet) the sustainability criterion is to be applied to. Then one must ask whether a separate sustainability criterion is necessary in practice: it will be very difficult to apply, and in any case improving conventional environmental policies will generally improve sustainability as an automatic side-effect.

If it is decided that improved environmental policy alone is not enough, and a separate sustainability policy is necessary, one must ask how it can be applied at both the system and project level. At the system level it is fairly clear, in theory if not in practice. Aggregate constraints (either economic or regulatory) must be imposed to slow down or halt the depletion of whatever resources have been shown to be important for sustainability. Such constraints will effectively drive up the price of such resources, to whatever level is necessary to induce the required conservation efforts throughout the system. These conservation efforts will be equivalent to providing intergenerational compensation in various ways. Moves toward this process are already clear with international agreements on CFCs.

Making sustainability operational at the project level is much harder, even conceptually. System sustainability cannot be disaggregated into project rules in the simple way that system optimality can be disaggregated into rules for cost-benefit analysis of projects. Many writers suggest that "intergenerational compensation" projects should be required for any group of projects that has a harmful overall effect on environmental resources. This is an attractive and fairly operational concept, but questions are raised as to how groups of projects are to be defined, how compensation should be paid, and who should pay it, particularly in the case of private investments. [Section 13]

Conclusions include the following. Many sustainability criteria are derivable from the same core ethic of intergenerational equity. Choosing a sustainability criterion that is appropriate to a given policy context requires judgments on which natural and man-made resources are significant inputs to production and welfare, and on how essential and substitutable they are. The notion that conventional environmental policies may improve sustainability is important. Suggestions for further work include more sophisticated models of growth with renewable resources; more analysis of how both poverty and environmental policy can affect discount rates; more work on the theory and practice of intergenerational compensation mechanisms at the project level; and more work on uncertainty and irreversibility. [Section 14]

ECONOMIC ANALYSIS OF SUSTAINABLE GROWTH AND SUSTAINABLE DEVELOPMENT

PART I: CONCEPTS

1. INTRODUCTION

1.1 The growing recognition of sustainable development as a policy goal

Sustainable development, and the interdependence of the economy and the environment, are increasingly important concepts to policymakers around the world. The concepts grew out of the "Limits to Growth" debate of the early 1970s (Meadows et al 1972, Cole et al 1973), which discussed whether or not continuing economic growth would inevitably lead to severe environmental degradation and societal collapse on a global scale. By the late 1970s and after much further debate (e.g. Pirages 1977, Cleveland 1979, Coomer 1979), an apparent resolution of the problem was reached: economic development could be sustained indefinitely, it was held, but only if development is modified to take into account its ultimate dependence on the natural environment.

This broad concept of "sustainable development" was first widely publicised by the World Conservation Strategy (IUCN, 1980). It has since become central to thinking on environment and development, and is espoused by many leaders of world stature. Notable recent examples are the report of the World Commission on Environment and Development (WCED 1987 - the "Brundtland Report"), and to the landmark World Bank paper "Environment, Growth and Development (World Bank 1987). The Brundtland Report vigorously promotes the idea of sustainable development, which it defines as:

"Sustainable development is development that meets the needs of future generations without compromising the ability of future generations to meet their own needs" (WCED 1987, p43)

and the World Bank is now committed to promoting sustainable development and to the proposition that

"economic growth, the alleviation of poverty, and sound environmental management are in many cases mutually consistent objectives." (World Bank 1988, p1).

1.2 Purpose of this paper

But what exactly is meant by various sustainability concepts such as sustainable development, sustainable economic growth, and sustainable resource use? Can one use a non-renewable resource sustainably, or is the concept limited to renewable resources? Does sustainability necessarily imply a more equal distribution of income within the current generation, as well as between generations? Is sustainability meaningful for developed as well as developing nations, and at the global or local as well as national levels? The answers to these questions are not at all clear. In Appendix 1 we have collected dozens of published definitions of sustainability concepts. The diversity of and conflicts between these definitions is self-evident, showing that sustainability is fast becoming a "motherhood and apple pie" concept, which

everyone supports but no one defines consistently. Indeed, "it may only be a matter of time before the metaphor of sustainability becomes so abused as to become meaningless" (O'Riordan 1988, p30).

Certainly, using a sustainability concept without providing a fairly detailed definition can easily lead to misunderstanding and confusion. This paper therefore sets out to:

- (1) categorise the various sustainability definitions in formal terms;
- (2) analyse the circumstances which may result in the various concepts of sustainability not being achieved;
- (3) analyse policies that might achieve sustainability (henceforth we will use "sustainability" as an umbrella term to cover a number of concepts; the precise concept intended will be made clear when necessary).

A particular feature is that the paper tries to provide a comprehensive view of sustainability which is applicable to developed as well as developing countries, and to non-renewable as well as renewable resources.

1.3 Methodology used

We do all this by building abstract models of optimal economic growth and development, using concepts from conventional ("neoclassical") economic analysis. Some of these concepts are more or less measurable (such as output, consumption, natural resources¹, and capital) and some are inherently non-measurable (such as utility and social welfare). The models are analysed mathematically to explore how these concepts relate to each other and how they grow over time. In particular we wish to distinguish circumstances where economic development and environmental protection are complementary, from circumstances where trade-offs have to be made.

However, all simple economic models, particularly optimal growth models, have several defects, as Robert Ayres has pointed out:

"Often the specified conditions are far from realistic, and the practical value of the exercise is slight until a great many simplified models, based on different assumptions, have been examined and the results

¹ The following classification of natural resources is implicit throughout this paper, with examples given in brackets:

- | | |
|--|---------------------------------|
| 1. Non-renewable materials (metals) | 3. Renewable materials (plants) |
| 2. Non-renewable energy (fossil fuels) | 4. Renewable energy (solar) |

Some resources can fall into more than one category: fossil fuels are also used as chemical feedstocks, plants can be used for fuel or food energy. We avoid the term **exhaustible resources**, because of possible semantic confusion. Some writers use to cover categories 1, 2 and 3 (category 4, solar energy, is clearly inexhaustible), but others restrict it to categories 1 and 2, arguing that since renewables can provide a sustained yield through natural growth they are not exhaustible.

compared. Even then, the truly generalizable statements are rare - and always subject to modification as a result of analysis of the next such small model. Regrettably, academic economists not infrequently generalize too freely from the results of ultra-simplified models." (Ayres 1978, p v; see also Koopmans 1977, p265)

We quote this at length so that the reader will not be disappointed by what follows. The assumptions are far from realistic; no numbers appear; results are only generalised "suggestions"; one cannot go on from this paper to say whether or not Burkina Faso (or wherever) is developing sustainably, and if not, why not and what policies would make development sustainable. But we contend that it is impossible to construct sustainability indices or build realistic simulation models of sustainable development, quite apart from the difficulty of collecting the necessary data, until concepts are better defined and understood by looking at simple models.

Even if somehow our models could be much more complete and realistic, they would still not be immune from criticism of a quite different kind from the above remarks by Ayres. Some writers question not whether neoclassical methods are tractable, but whether it is even appropriate to use neoclassical concepts in the context of sustainable development and intergenerational equity. We discuss this in Section 2.4, after we have expounded our general neoclassical model.

Whether or not it is necessary to have models of sustainable development at all is yet another matter, one we defer till Section 7 for reasons that will become clear. One good reason to try is surely to limit the kind of terminological abuse that would debase sustainable development into a useless phrase, as O'Riordan (1988) fears.

1.4 Structure of the paper

The structure of the paper is as follows:

Section 2 sets up a general quantitative model of the economy and the environment, and discusses possible objections to the neoclassical assumptions built into the model.

Section 3 uses the general model to define the various sustainability concepts, stressing the difference between survivability and improvement, and the common idea of sustainability as maintaining capital.

Section 4 discusses the uses and shortcomings of optimal growth methodology in analysing economy/environment models and sustainability.

Sections 5-9 all use radical simplifications of the general model:

Section 5 looks at economy/environment tradeoffs in a static world, where resource inputs are ignored, and a given output is divided between consumption and pollution control expenditure.

Section 6 (with mathematical details in Appendix 2) assumes a single, non-renewable resource input ("cake") and a given rate of technical progress, and compares sustainability and optimality as criteria for allocating resource consumption over time.

Section 7 (Appendix 3) builds on Section 6 by allowing output or utility to

depend on the total resource stock, and looking at the effects of government policy instruments on conservation and depletion.

Section 8 (Appendix 4) introduces man-made capital, and discusses the substitution between capital and resources and possible limits on this substitution.

Section 9 (Appendix 5) assumes a single renewable resource ("corn") and a minimum consumption level needed for survival, and discusses the interaction of poverty, resource degradation and outside assistance.

Section 10 addresses the role of a more equal income distribution and of meeting basic needs as part of sustainable development.

Section 11 asks whether discount rates can be too high to achieve sustainability, and distinguishes the moral and economic cases for lower discount rates.

Section 12 briefly looks at the way imperfect information, particularly inherent uncertainty about the distant future, can affect sustainability.

Section 13 looks at whether or not sustainability concepts can be translated into operational procedures at the economy or the project level, paying particular attention to mechanisms for "intergenerational compensation".

Section 14 draws some conclusions and suggests directions for further work.

One prominent issue that is hardly touched upon is sustainability and international trade. We hope to address this in a later paper.

1.5 Some issues to be addressed

To what the appetite, the following issues will be addressed, in addition to those inherent in the above section descriptions:

- o Is sustainable development a process or a state? (Sections 3, 10)
- o Does sustainable resource use require that every resource stock must not decline? What is the relevance of natural resource accounting? Is sustainable resource use a means or an end? (Sections 3, 9)
- o What distinguishes a case where economic growth and environmental improvement are mutually consistent objectives from one where they are not? (Sections 5, 7)
- o How much can sustainable development be furthered by merely defining and enforcing property rights over the environment, and how much do such rights need to be changed? (Section 7)
- o Will lower discount rates lead to too little or too much investment for sustainable development? Is investment good or bad for the environment? (Sections 6,8,11)

2. MEASURING THE ECONOMY AND THE ENVIRONMENT

Here we set out a formal and fairly general model of the economy and its surrounding environment. To address sustainability issues it is necessary to

include the environment, even if we are not interested in environmental issues for their own sake. If instead we use a conventional 1960s model of economic growth, in which output is produced from just capital and labour inputs and is freely disposed of after use, we have little reason to suppose that sustainability should ever be a problem (unless savings rates are insufficient to maintain the capital stock). The resulting complexity of our model is daunting, but is needed in Section 3 in order to analyse the dozens of different definitions of sustainability listed in Appendix 1. We then revert to much simpler models for later sections, but the greater realism and complexity of this section should be borne in mind throughout. The importance of aggregation problems is emphasised by disaggregating output, labour, natural resources etc into several different classes. The number of classes (m) may vary, e.g. m_1 different goods, m_2 different resources, etc. Table 1 sets out the fairly obvious vector notation that is used in the model.

TABLE 1 VECTOR NOTATION USED IN THE ECONOMY-ENVIRONMENT MODEL

\underline{c}	(vector)	means $\{c_1, c_2, \dots, c_m\}$; also written $\{c_j\}$; $j = 1, \dots, m$
And if \underline{p} is also a vector of m numbers, then		
$\underline{p} \cdot \underline{c}$	(= C say, a scalar)	means $\sum p_j c_j$; $j = 1, \dots, m$
$\min \underline{c}$	(scalar)	means $\min \{c_j\}$; $j = 1, \dots, m$
non-declining \underline{c}	(vector)	means $\dot{c}_j \geq 0$, for all $j = 1, \dots, m$ and for all time
non-declining C	(scalar)	means $\dot{C} = d(\sum p_j c_j)/dt \geq 0$, for all time

Note the difference between the vector and aggregate scalar measures, for example with regard to natural resource stocks. Non-declining \underline{s} means that every resource stock is constant or growing; non-declining S means only that the aggregate resource S, computed using a vector of "resource weights" \underline{v} such that $S = \underline{v} \cdot \underline{s}$, is conserved; individual resources (e.g. plant or animal species) may be declining, perhaps to extinction. The ultimate purpose of resource accounting is to measure not just \underline{s} but also \underline{v} , so that we can say something meaningful about aggregate resources. Here we ignore the problem of just how difficult such measurement is in practice, and assume that we can define all the individual quantities needed to describe the economy physically in Section 2.1, the weights or values and the resulting aggregates or totals in Section 2.2, and some general functional relationships in Section 2.3.

2.1 Individual physical quantities

In the model there are m_1 types of output, with total outputs \underline{q} divided into consumption \underline{c} , investment in physical capital (machines, etc) \underline{i}_k , investment in technology and human capital \underline{i}_r , and clean-up expenditure \underline{x} :

$$\underline{q} = \underline{c} + \underline{i}_k + \underline{i}_r + \underline{x}$$

Investments \underline{i}_k accumulate to form physical capital stocks \underline{k} , and investments \underline{i}_r accumulate to form stocks of technical knowledge \underline{r} . We assume that all outputs are "goods" in the sense that they do not represent costs or defensive expenditures. We thus abstract from the frequent criticisms that GDP measures include such items in practice (see for example Daly 1988).

There are m_2 types of natural resources (usually abbreviated to just "resources"). Resource stocks \underline{s} are classified into \underline{s}_a , the first m_{2a} resources which are renewable ("alive"), and \underline{s}_n , the last $(m_2 - m_{2a})$ resources which are non-renewable, thus:

$$\underline{s} = \{\underline{s}_a, \underline{s}_n\}$$

The corresponding resource flows are similarly classified into renewable and non-renewable components: $\underline{r} = \{\underline{r}_a, \underline{r}_n\}$

Now many renewable resources are of no direct instrumental value to man, either as sources of amenity or sources of economic production. However, the intricate cycles of food, energy and nutrients within ecosystems ensure that many non-instrumental species and resources are vital to the existence of other species that are directly valuable. Our measure of renewable resource stocks \underline{s}_a must therefore be extended to include not only the valuable species (for example, trees in a forest) but also the resources necessary to support them (for example, soil and bacteria to provide nutrients, insects and birds to provide pollination).

There are m_3 pollution stocks \underline{p} and flows \underline{d} ("disposal")

Lastly, there are m_4 groups of people. We make no distinction here between population, numbers of households and numbers of workers, and denote the population groups by the vector \underline{l} .

Note two major simplifications in the above: imports and exports are omitted, and natural resources are not subdivided into materials and energy.

2.2 Weights and aggregates

Note: assuming that all these weights exist - particularly weights for aggregating individual utilities into social welfare - bypasses enormous theoretical and practical problems.

There are m_1 goods prices \underline{g} , hence $Q = C + I_k + I_r + X$ where:

aggregate output	$Q = \underline{g} \cdot \underline{q}$
consumption	$C = \underline{g} \cdot \underline{c}$
capital investment	$I_k = \underline{g} \cdot \underline{i}_k$
technology investment	$I_r = \underline{g} \cdot \underline{i}_r$
clean-up	$X = \underline{g} \cdot \underline{x}$
capital	$K = \underline{g} \cdot \underline{k}$
technology	$T = \underline{g} \cdot \underline{r}$

There are m_2 resource values $\underline{v} = (\underline{v}_a, \underline{v}_n)$

hence aggregate resource stock	$S = \underline{v} \cdot \underline{s}$
renewable resource stock	$S_a = \underline{v}_a \cdot \underline{s}_a$
non-renewable resource stock	$S_n = \underline{v}_n \cdot \underline{s}_n$
resource flow	$R = \underline{v} \cdot \underline{r}$
renewable resource flow	$R_a = \underline{v}_a \cdot \underline{r}_a$
non-renewable resource stock	$R_n = \underline{v}_n \cdot \underline{r}_n$

There are m_3 "toxicity coefficients" or other measures of waste harmfulness \underline{h} ,

hence aggregate pollution stock	$P = \underline{h} \cdot \underline{p}$
pollution flow	$D = \underline{h} \cdot \underline{d}$

Where convenient, we may also use m_2 resource environmental values \underline{e} to compute:

overall environmental quality $E = \underline{e} \cdot \underline{s} - P$

There are m_4 measures of labour productivity \underline{z} , per capita consumption \underline{w} , per capita utility \underline{u} and class utility weights \underline{f}

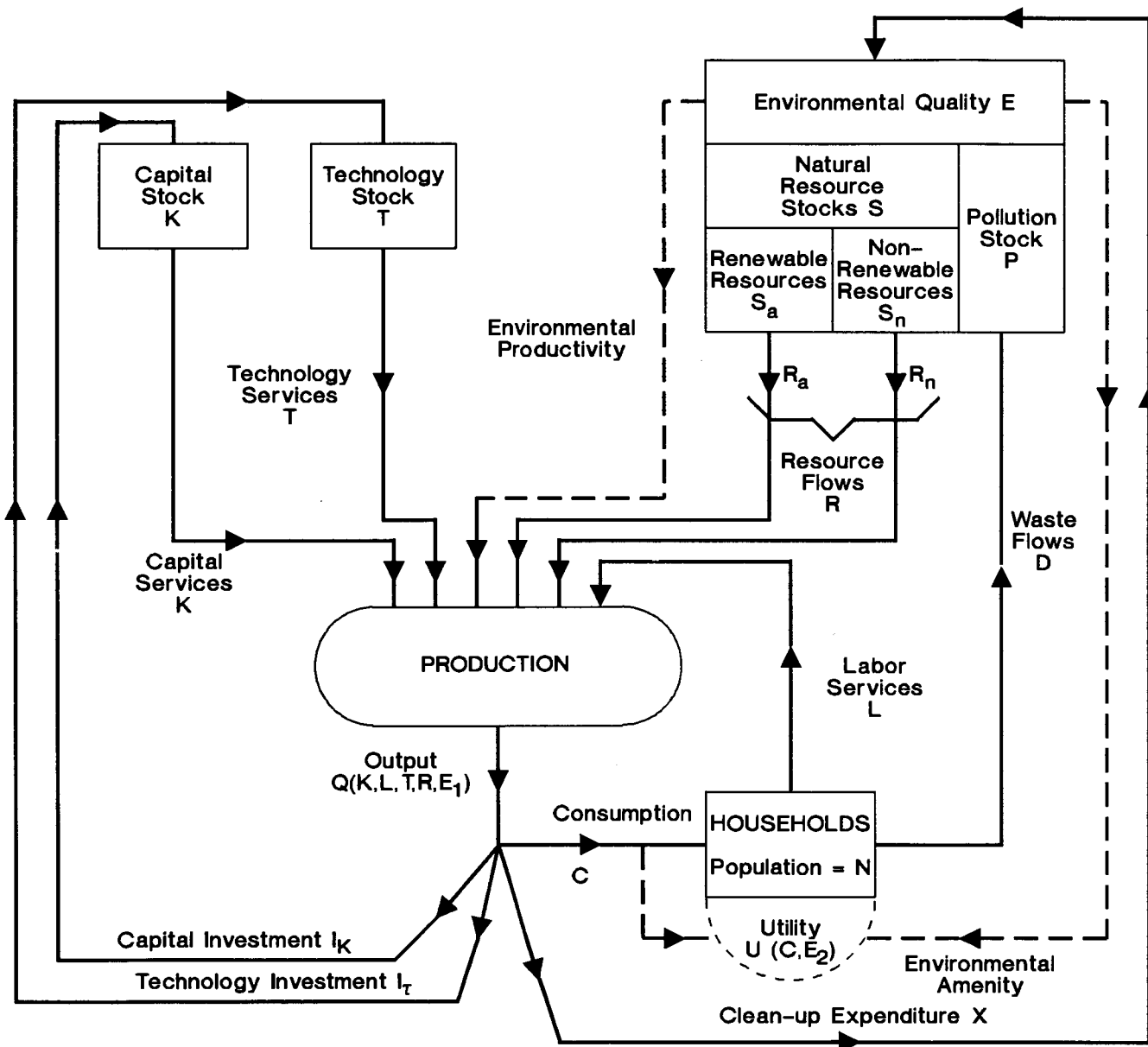
hence aggregate population	$N = \sum l_j$
labour input	$L = \underline{z} \cdot \underline{l}$
consumption	$C = \underline{w} \cdot \underline{l} = \underline{g} \cdot \underline{c}$
social welfare	$U = \underline{f} \cdot \underline{u}$

2.3 Functional Relationships; Environmental Productivity and Amenity

Most relationships between variables in the model properly be described by vector relationships. For example, the population growth of one species (an element of \underline{s}_a) would depend on the stocks of many other species and on inanimate resources and pollution (other elements of \underline{s}_a , \underline{s}_n and \underline{p}). However, for the rest of this paper, there is no point in using vector and matrix algebra to describe these relationships, so below we shall just describe scalar relationships between aggregates; but this is already a simplification. A dot over a symbol represents a time derivative, and a + or - above an independent variable shows whether or not increasing that variable increases or decreases the dependent variable. All functions are assumed to be continuously differentiable with respect to their arguments. Figure 1 depicts aggregate relations in our general economy-environment model. "Stripped-down" versions of this Figure appear in several later sections to illustrate the more restricted models used there.

The production of output depends on capital, labour, resource inputs, technology, and also on the "state of the environment". The environment, which consists of the stocks of resources S and pollution P , can clearly be

Figure 1: ECONOMIC AND ENVIRONMENTAL STOCKS AND FLOWS – A GENERAL MODEL



aggregated in many different ways, and we often find it convenient to use E_1 to represent the environmental aggregate that affects production. E_2 will be a different environmental aggregate that affects amenity values, or we may also sometimes ignore this difference between environmental aggregates and simply use an all-purpose measure E of environmental quality. The dependence of production on the environment is hereafter called "environmental productivity".

$$Q = Q(K, L, T, R, S, P), \text{ which is simplified to } Q(K, L, T, R, E_1) \text{ in Figure 1}$$

The growth of both capital and technology equals gross investment minus depreciation (the depreciation coefficients δ_k and δ_r are unrelated to the social utility discount rate δ in Section 3):

$$\dot{K} = I_k - \delta_k K \qquad \dot{T} = I_r - \delta_r T$$

The growth of resources equals natural growth (which is zero for non-renewable resources) minus resource extraction:

$$\dot{S} = G(S, P) - R$$

The growth of pollution stock equals the rate of waste disposal minus an assimilation term which represents both natural assimilation and the ameliorative effects of clean-up expenditure:

$$\dot{P} = D - A(P, X)$$

The growth of the human population depends on natural growth, and in a complex way on consumption income:

$$\dot{N} = N(L, C)$$

Labour productivity can be affected by consumption and the environment

$$L = L(C, S, P)$$

Lastly, "utility" or "social welfare" depends not only on consumption², but also on the state of the environment. This is the "environmental amenity" effect:

$$U = U(C, S, P), \text{ which is simplified to } U = U(C, E_2) \text{ in Figure 1.}$$

In practice, the boundary between the amenity and productivity effects of the environment is not always clear because the boundaries of commercialisation is

² It is normal to assume that social welfare U depends on per capita consumption $c = C/N$ rather than total consumption C . We make this distinction only in Section 9 where population N is assumed to vary; elsewhere population is assumed constant, and it is unnecessary to distinguish between C and c .

variable. If I refrain from strolling in a public park because the day is smoggy, that is an amenity effect; but if I refrain from paying to enter an amusement park for the same reason, that is a productivity effect.

It is worth noting in passing that it has not always been accepted that environmental resources have a significant role to play in models of economic growth. Until the general reawakening of environmental awareness in the late 1960s, economic output was considered to require only capital, labour and technology inputs (with technology recognised as a separate input only in the mid-1950s). Figure 2 represents the kind of model used then, and Burmeister and Dobell (1970) give a good summary of growth models of this type.

In Section 3 we examine what objective function(s) the optimal control process is meant to maximise, and what constraints it is meant to observe. In Section 4 we then discuss the extent to which these functional relationships can be analysed using optimal control models, and what results can be drawn from such analysis. However, we must first address some fundamental criticisms of the very form and concepts of our model.

2.4 Criticisms of the neoclassical paradigm.

The above model incorporates a wide range of assumptions from neoclassical thinking that many have challenged, both generally and in discussions specifically on intergenerational equity and sustainable development. These criticisms focus particularly on the form of the utility or social welfare function $U(\cdot)$, but also on the production function $Q(\cdot)$.

(a) Many writers on sustainability question the inbuilt assumption that the functional form $U(\cdot)$ is determined exogenously, i.e. that tastes and preferences appear when we are born and are not formed by culture, education or advertising. For example, WCED (1987, quote 4) holds that "perceived needs are socially and culturally determined", and that:

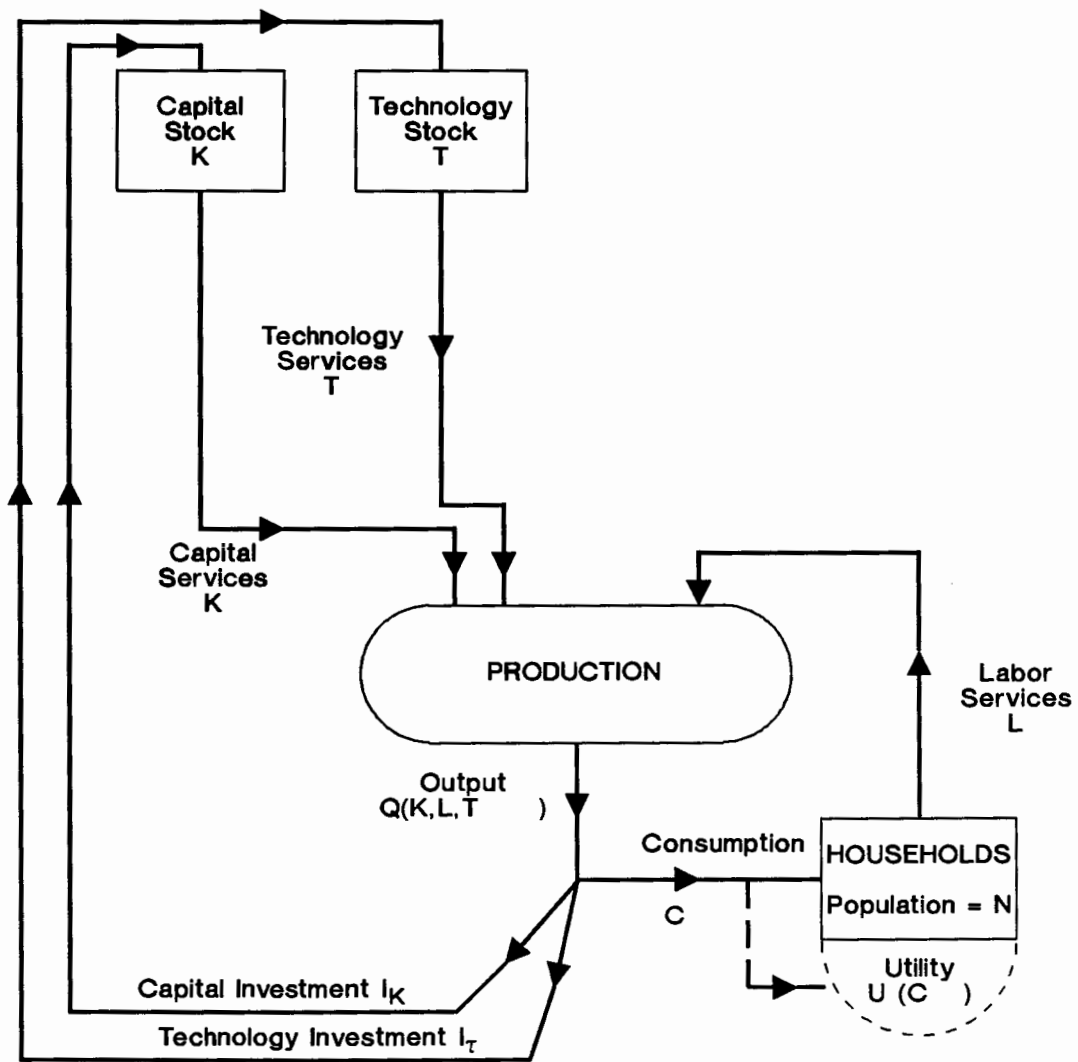
"The changes in human attitudes that we call for depend on a vast campaign of education, debate and public participation." (WCED 1987, p23)

(b) A related point is made by the evolutionary school of economics (see for example Norgaard 1984, 1985). This school holds that the forms of economic functions change irreversibly over time, in a way that depends upon the future path of the independent variable C , E , etc. This holds for both utility and production functions.

(c) Another questionable assumption in $U(\cdot)$ is that individuals derive happiness from absolute, rather than relative, levels of individual consumption and environmental quality. If position relative to others is all that really matters (as suggested in some exploratory work by Easterlin 1974), changes in aggregate variables C , S and P would have little effect on aggregate utility U . Similar problems occur if change relative to expectations is what matters (Rescher 1980).

(d) Many authors would criticise our utility function for leaving out important, if inherently unquantifiable variables such as "cultural

Figure 2: A PURELY ECONOMIC MODEL



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disruption and social instability" (Barbier 1987) and "basic freedoms" (Pearce, Barbier and Markandya 1988).

- (e) Yet more fundamental criticisms of our neoclassical functions are that the trade-offs or substitutions that they allow may be psychologically impossible or morally inexcusable. Page (1983) sets out these criticisms at length. The existence of a differentiable $U(C,E)$ function implies that we can make mental tradeoffs such as working out how much extra consumption we would require to compensate for a substantially increased risk of cancer due to higher radiation levels in the environment. Page questions whether or not it is possible to answer such a question sensibly. Moreover, he questions whether or not the current generation has the right to attempt to answer it on behalf of future generations as yet unborn. Have we the right to degrade the natural environment for future generations, and offer them increased man-made capital and technological knowledge (enough to lead to increased production, even though natural resources will be depleted) as compensation? Page answers no: the natural resource base cannot be "justly acquired" through human labour in the way than machines can. Therefore we are not morally free to treat natural resources as mere factors of production that can be depleted and substituted for by man-made capital. A related criticism is that the pure time discounting, as measured by the utility discount rate δ in the following section, has no moral justification. Criticisms of time discounting are also made by Parfit (1983) and are reviewed by Markandya and Pearce (1988a, 1988b).

These criticisms can only be listed here, since by definition they cannot be incorporated in our neoclassical model. The questions of substituting capital for resources arise again in Section 3.11, but there the discussion focuses not on whether such substitution is morally allowable, but on the extent to which it is physically possible.

3. DEFINITIONS OF GROWTH, DEVELOPMENT AND SUSTAINABILITY CONCEPTS

3.1 The context of sustainability

We can now use the concepts from the above economy-environment model to attempt precise neoclassical definitions of growth, development and sustainability concepts. Table 2 lists a selection of definitions, inspired by the quotations collected in Appendix 1 (most of the references below are to these quotations); clearly many more definitions are possible.

Sustainability has been applied to a vast array of situations, ranging from the conditions for success of a World Bank agricultural development project to the problem of creating conditions for the improvement of the situation of the whole human race in the "further future" (Kneese and Kopp 1988). Clearly an appropriate criterion for sustainability will depend very much upon the context, especially if it is to be used operationally. An attempt is made in Section 3.11 to show how diverse sustainability criteria can be derived from unifying general concepts such as "maintaining the stock of capital" or "ensuring non-declining utility".

TABLE 2. POSSIBLE DEFINITIONS OF GROWTH, DEVELOPMENT AND SUSTAINABILITY

See Section 2 for most notation. Additional notation is $\delta > 0$ is social discount rate; t is time; $T > 0$ is lifespan of a generation; and subscripts bn = "basic needs"; sub = "subsistence"; es = "ecologically sustainable" All survivability and sustainability concepts apply for all time.

Economic growth	= increase in Q or C
Development (process) I	= increase in $U = U(C,S,P)$
Development (process) II	= increase in \underline{c}
Development (state) III	= $\min \underline{c} > c_{bn}$
Optimal path	= path maximising $\int_0^{\infty} U(t)e^{-\delta t} dt$
Survivable growth	= $\min \underline{w} > w_{sub}$
Sustainable growth I	= non-declining Q (or C)
Sustainable growth II	= positive and non-declining \dot{Q}/Q or \dot{C}/C
Survivable development	= $\min \underline{w} > w_{sub}$ and $G < G_{es}$
Sustainable development I	= non-declining U
Sustainable development II	= non-declining U , and with $\min \underline{c}$ increasing
Sustainable development III	= non-declining U , and with $\min \underline{c} > c_{bn}$ and $\max \underline{c} < c_{es}$
Sustainable resource use I	= non-declining \underline{s}_a
Sustainable resource use II	= non-declining S_a
Sustainable resource use III	= non-declining S
Sustainable resource use IV	= non-declining \underline{s}_a and non-increasing p
Lifetime sustainability	= instead of nondeclining X (whatever X is),
non-declining $\int_t^{t+T} X(r)e^{-\delta r} dr$	- i.e. present value of X for generation at time t with a time horizon stretching T years into the future

Three remarks apply to almost all sustainability criteria:

- (a) They are long term criteria. Although "sustaining economic growth" by using skilful macroeconomic management to avoid short term cycles of unemployment, inflation, and trade deficits is clearly of prime policy importance, it is not our concern here, and we assume throughout that all factors of production are "fully" employed.
- (b) Most criteria derive from a common school of ethical principles regarding intragenerational and/or intergenerational fairness or justice. The biggest single inspiration for this school has undoubtedly been the work of Rawls (1971). However, other ethical views of intergenerational justice exist and should not be overlooked; Pearce (1983) and d'Arge (forthcoming) give useful analyses.
- (c) Sustainability criteria are mostly mathematical inequalities and are therefore constraints, rather than maximising criteria like optimality. We explore this difference in Section 4.2.

3.2 Growth and development

Economic growth is uncontroversially defined as rising aggregate consumption C or output Q . As long as the average propensity to consume (C/Q) is constant the distinction is unimportant. Note that growth is measured in value, not physical units: a growth of economic output does not necessarily mean a growth in physical throughput of materials and energy. The problems start in defining development to make up for the shortcomings, identified by Redclift (1987) and countless others, that growth ignores environmental quality and other social factors, and also ignores the distribution of income. Table 2 gives three possible definitions of development, two of development as a process, one as a state. Many other definitions are possible. In this formal context we cannot represent ideas, such as in Daly (quote 2), Georgescu-Roegen (quote 1) or Boulding (1988), that development is qualitatively different from growth.

3.3 Optimality

The conventional optimality formula of maximising the present discounted value of utility is widely accepted, although it does make sweeping assumptions: for example, that intertemporal preferences are consistent (Strotz, 1956) and well-known into the distant future. It can be applied to either growth, if $U = U(C)$, or development definition I in Table 2, if $U = U(C,S,P)$. There is a semantic problem in that some writers regard "optimality" as defining the ultimate social goal, and would incorporate other any constraints such as sustainability into their definition of optimality. This is understandable, but confusing for our purposes; here we restrict "optimality" simply to mean present value maximisation. The time horizon chosen can be finite, although we stick to infinity here. Most dynamic optimisation models ignore environmental amenity and assume $U = U(C)$, but there are plenty of models that do include amenity as $U = U(C,S)$ or $U(C,P)$ (for examples see d'Arge and Kogiku 1973, Vousden 1973, Forster 1973, Maler 1974, Lusky 1975, Becker 1982, Krautkraemer 1985 and 1986).

3.4 Survivability versus sustainability

We then come to the question of **survivability versus sustainability**. There are some optimal growth modellers (e.g Kemp et al 1984) who regard sustainability as meaning simply that consumption is kept above some subsistence minimum. However, most other definitions understand sustainability to mean sustaining an improvement (or at least maintenance) in the quality of human life, rather than just sustaining the existence of life - see Allen 1980, quote 4; Brown et al 1987; Clark 1986; Markandya and Pearce, quote 2; Repetto 1985, quotes 1 and 3; Tietenberg 1984; and WCED 1987, quote 1. Simply requiring that the future exists may be manifestly unfair, since it would allow an opulent present followed by a Spartan but survivable future. This is why we choose the distinction between survivability and sustainability set out in Table 2 and illustrated in Figure 3. Our standard definition of sustainable development will be definition I - non-declining per capita utility - because of its self-evident appeal as a criterion for intergenerational equity.

However again, this is not the end of the matter. One important advantage of survivability is that it is objective. One can in principle make physical calculations of the minimum amounts of food, shelter, clean air and water needed to keep an economy of a given number of people alive, or, somewhat more comfortably, provided with "basic needs"; whereas improvements in utility or the "quality of life" will always be non-market value judgments and thus much harder to measure operationally. For poor, natural resource-based countries the minimum supplies must be provided the ecosystem. (For other countries this is less clear: many developed countries use exports of manufactures and services to buy necessary food and raw material imports, although to suggest that every country could do this would clearly be a fallacy of composition.) We can then calculate, subject to detailed scientific debate, the minimum size and composition of the ecosystem needed to guarantee survivability.

3.5 Sustainable use of renewable resources

In natural resource-based economies, sustainability can often be reduced to somewhat simpler and more operational concepts of **sustainable resource use**, such as those listed in Table 2. If a country is very poor, with virtually no capital or non-renewable resources, it is totally reliant on its renewable resource base. Simple survival will then matter far more than concerns about environmental amenity, and survival will depend upon the sustainable use of the resource base. But does this then mean that every resource must be conserved, as in definition I in Table 2? Does it mean that the conversion of large forests in North America and Europe to farmland in earlier centuries was unsustainable? Such absolutism seems unnecessary from an anthropocentric point of view, as Repetto (1985, quote 2) and WCED (1987, quote 5) recognise. Trade-offs between different resources can in principle be calculated using appropriate weights, ending up with Table 2's definition II of sustainable resource use; although the theoretical and practical problems of resource accounting methodologies to find these weights or "resource values" are legion (Repetto and Magrath, 1988; Ahmad et al, forthcoming). A slightly different approach appears in the work of Barbier, Markandya and Pearce. Some wording,

Figure 3: OPTIMALITY, SUSTAINABILITY AND SURVIVABILITY

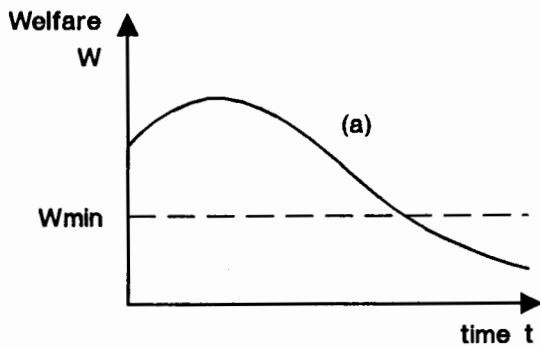
Formal distinctions between OPTIMAL, SUSTAINABLE and SURVIVABLE development paths of welfare $W(t)$ over time t are:

OPTIMAL $W(t)$ maximizes $\int_0^{\infty} W(t)e^{-\delta t} dt$ (PRESENT VALUE)

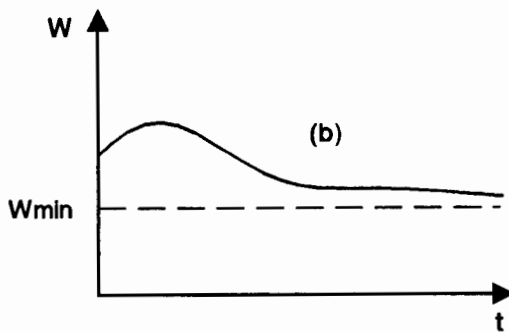
SUSTAINABLE $W(t)$ is such that $\frac{dW}{dt} = \dot{W} \geq 0$ for all time

SURVIVABLE $W(t)$ is such that $W \geq W_{min}$ for all time

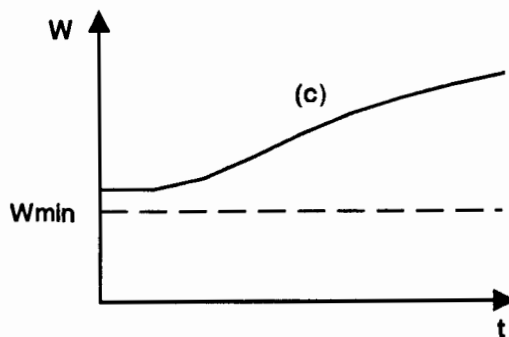
EXAMPLES



Path might well be OPTIMAL, but is NOT SUSTAINABLE and also NOT SURVIVABLE.



Path might well be OPTIMAL, but is NOT SUSTAINABLE although it is SURVIVABLE.



Path might well be NON-OPTIMAL, but it is SUSTAINABLE and SURVIVABLE.

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for example the argument in Pearce (quote 2) for "constraints which set resource harvest rates at levels no higher than managed or natural regeneration rates", might seem to imply that individual resources should be protected absolutely. However, in Pearce et al (1988) it becomes clear that the concern is to conserve the total stock of natural resources, although there are several bases (prices, values, physical measures) for calculating the total stock, and natural threshold and irreversibility effects may impose severely limit the tradeoffs that can be allowed between different resources without threatening sustainability. Technical limits to substitutability are also discussed in Sections 3.11 and 8.2. Allen (1980, quotes 2 and 3) points out that different resources will need protecting in different countries. This seems a fruitful area for further analysis.

Further questions arise if a poor country has non-renewable resources, or is suffering from pollution. Turner (quote 4) seems to dismiss the concept of sustainability for non-renewables, but this ignores or at least assumes severe limits on the roles of technical progress or capital accumulation, as is shown in Sections 6 and 8. In any case, an extended definition of sustainable resource use would be necessary: definitions III and IV are some of the many possible variations.

3.6 Maintaining the effective resource base

Yet another concept of sustainable resource use, is that of **maintaining the economy's effective resource base** (Howe 1979, quote 1). This was originally framed for non-renewable rather than renewable resources, and although Howe attributes the concept to Page (1977), there is an important difference between the two writers here. Page proposed the criterion of a constant real price index for virgin materials, which makes no allowance for capital accumulation or technical progress which may in principle reduce the amount of materials needed to produce a given amount of economic output. In contrast, Howe focuses on the economic productivity of the whole resource base is maintained, rather than the physical stocks of individual or aggregate resources. This is achieved by balancing resource depletion with capital accumulation and technical progress. Depending on how we define "value", and provided we work in a general equilibrium context, we show in Appendix 3 how this latter concept can be made exactly equivalent to our standard definition of sustainability as non-declining utility. The contrast between the two approaches is discussed further in Section 3.11.

3.7 Deep ecology and non-instrumental sustainability

Definition I of sustainable resource use also follows from a **deep ecology** ethic, which holds that other species have an inherent right to a sustained existence, independent of their instrumental value to man. This point of view is reflected in O'Riordan (quote 2) - who calls this notion simply "sustainability", which causes confusion - Turner (quote 5) and WCED (quote 6); it is also discussed in Pearce (1987). It is a point of view that many scientific studies of sustainable ecosystems adopt, although usually shrouded in the notion of preserving the "scientific value" of species and ecosystems. The now widely-recognised concept of "existence value", wherein people "place a value on the mere existence of biological and/or geomorphological variety

and its widespread distribution" (Krutilla 1967), is partly relevant here, since it involves no direct use of resources. Nevertheless its anthropogenic origin would probably make us classify existence value as an extension of "environmental amenity".

3.8 Intergenerational equality

Another fairly absolute concept is that of strict intergenerational equality, the criterion that logically follows from the Rawlsian maximin criterion of justice. Solow (1974b), Hartwick (1977), and the many papers based on these two all use a constant (not rising) consumption path as their criterion for intergenerational justice. They show how, given certain assumptions, constant consumption can be maintained by following Hartwick's Rule: all rents from depleting non-renewable resources are invested in reproducible (man-made) capital which substitutes for resource inputs in the production function. The assumption that constant consumption ensures intergenerational equity ignores any environmental amenity effects that may result from natural resource capital being replaced by man-made capital.

Intergenerational equality features hardly at all in discussions on sustainability, so it does not appear in Table 2. It has limited appeal because the present generation lives on for a finite time into the future, and so may itself prefer a future with growing welfare to one with constant welfare. Nevertheless Hartwick's Rule may be useful for achieving sustainability in some circumstances, and the Hartwick literature provides a useful interpretation of intergenerational equality in terms of maintaining the capital stock intact (recently noted by Solow 1986, and discussed further in Section 3.11 below).

3.9 Income distribution

We now turn to the question of intragenerational equity, better known as **income distribution**. It is clear from Allen (quote 2), Goodland and Ledec (quote 1), Porritt (1984, passim), Tolba (quote 1), WCED (quotes 1-3) and the World Bank (quotes 1-3), that many regard alleviating poverty, both within a nation and between nations, as an integral part of sustainable development. No system of weights, which can theoretically compute an increase in social welfare U whilst the poor get poorer, is acceptable to this point of view; and definition II in Table 2 reflects this. WCED (quote 4) goes further, and seeks curbs on any high living standards which would be physically impossible for everyone to have. This point of view, including the notion of development as a state as well as a process, is reflected in definition III of sustainable development.

3.10 Definition of a future generation

Finally, it is important to reflect on what is meant by a "future generation". Most of the current generation of decision makers expect to stay alive for several decades more, and may be willing to make sacrifices for a while in return for a better future. Therefore a more appropriate measure of a generation's welfare would be discounted utility over an appropriate time horizon of T years to come, rather than utility at just one point in time.

This is reflected in the **lifetime sustainability** criterion in Table 2, taken from Riley (1980). We do not need to use this more sophisticated criterion for our simple models below, but it is important to bear it in mind.

3.11 Sustainability as non-declining utility or non-declining capital

In conclusion to Section 3, unless otherwise stated, we hereafter use **definition I** of sustainable growth (non-declining consumption C) and **definition II** of sustainable development (non-declining utility U). How can these definitions be related to the several conditions for sustainability quoted in Appendix 1 that specify some capital stock should be preserved? Two such sustainability conditions, although very different ones, are:

"...a society that invests in reproducible capital the competitive rents on its current extraction of exhaustible resources, will enjoy a consumption stream constant in time [and hence achieve intergenerational equity]. ...this result can be interpreted as saying that an appropriately defined stock of capital - including the initial endowment of resources - is being maintained intact, and that consumption can be interpreted as the interest on that patrimony." (Solow 1986, p141).

"We summarise the necessary conditions [for sustainable development] as 'constancy of the natural capital stock'. More strictly, the requirement is for non-negative changes in the stock of natural resources such as soil and soil quality, ground and surface water and their quality, land biomass, water biomass, and the waste assimilation capacity of receiving environments." (Pearce, Barbier and Markandya 1988, p6)

Our discussion here centres on the substitutability of various inputs for each other in both the production function $Q(K, R_n, R_a, T, E_1)$ and the utility function $U(C, E_2)$. (We have again conflated natural resources S and pollution P into two environmental aggregates E_1 and E_2 , which differ because different parts of the natural environment are important to amenity and to productivity; we also ignore labour input L.) The perspective is neoclassical in the sense that doubts in Section 2.4 about the moral validity of substitution are ignored, but crucial doubts are raised about the normal neoclassical assumptions about the technical feasibility of substitution. We quote the above papers as recent and fairly representative examples of broad "neoclassical" and "ecological" schools of thought on sustainability.

Solow's condition of a constant capital stock (including non-renewable resources) can readily be derived from a constant utility criterion. His implicit utility function ignores environmental amenity: $U = U(C)$ only, so constant utility U requires constant consumption C. His production function ignores renewable resource flows R_a and the environmental stock E_1 :

$Q = Q(K, R_n, T) = K^a R_n^b e^{mt}$, a Cobb-Douglas function. As non-renewable resources R_n are depleted, man-made capital K must be built up to substitute for

resources in the production process. The mathematically "smooth" nature of the Cobb-Douglas functions assumed by Solow and other neoclassical writers

such as Stiglitz (1974) ensures that such substitution is always technically feasible. Solow then shows that maintaining a constant C requires some aggregate stock of K and R_n to be preserved by choosing a certain level of investment $I (= Q - C)$.

The analysis of Pearce et al is not presented as a mathematical model, so the following formal interpretations are necessarily more open to debate. Their definition of sustainability is also to sustain output Q , and they also make no mention of the environment as a source of amenity. However, their necessary condition for sustainability is that the productive natural capital stock E_1 be preserved, so this should also ensure that utility $U = U(C, E_2)$ is preserved, given the similarity of environmental measures E_1 and E_2 .

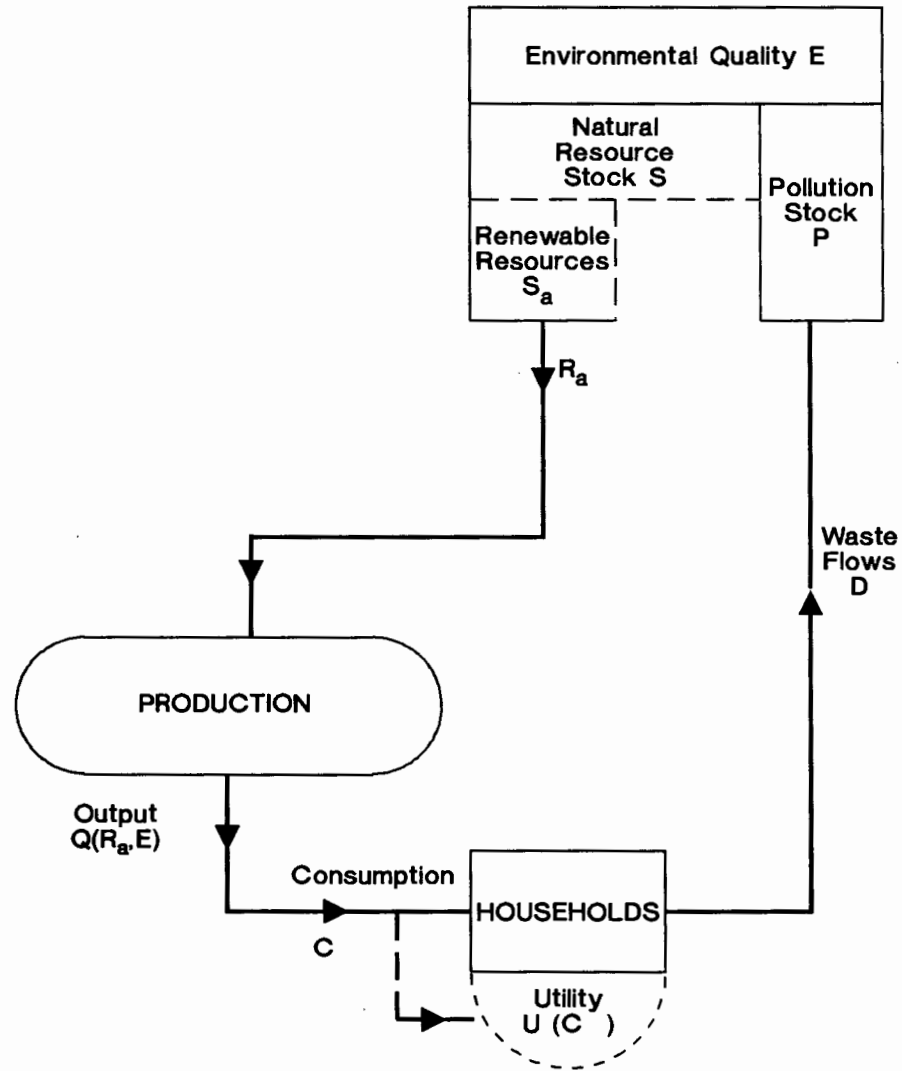
The real interest is in how Pearce et al reach their sustainability condition. In places it might appear that they are assuming that renewable inputs and the state of the environment are the only inputs that really matter, so that $Q = Q(R_a, E_1)$ and the economy-environment model looks like Figure 4. Maintaining a non-declining Q would then obviously require that the natural capital stock E_1 (from which the flow R_a is also derived) is preserved. However, a closer reading shows that they do acknowledge that technology, non-renewable resources and man-made capital clearly have some role in production; but their implicit production function is not neoclassically smooth. They stress that:

"...natural capital differs from man-made capital in a crucial respect. Man-made capital is virtually always capable of symmetric variation - it can be increased or decreased at will. Natural capital is subject to irreversibilities in that it can be decreased but not often increased if previous decrements led to extinction. ...natural and man-made capital are substitutes only to a limited extent." (Pearce, Barbier and Markandya 1988, p15, emphasis in original)

Hence, if natural capital is already depleted to the point where irreversible damage may be caused, a necessary (but perhaps not sufficient) condition for sustainability is that natural capital is conserved; man-made capital, technology or non-renewable resources are no substitutes in such a situation.

The differences in the neoclassical and ecological approaches to sustainability - Solow assumes away any technical limits to substitutability and ignores the biosphere, whereas Pearce et al emphasise "threshold effects" and "critical minimum stocks" [of natural capital], and give the biosphere pride of place - are to some extent explained by the difference in context. Solow is explicitly concerned with developed nations using non-renewable resources (he uses the depletion of North Sea oil as his example), whereas Pearce et al focus on microeconomic decisions in developing countries. Renewable resources are relatively unimportant in developed countries and relatively more important in developing countries, and this may well affect the degree to which renewables can be substituted for by man-made capital. But we doubt whether it is sufficient to reconcile the stark differences in the two approaches, and feel the whole question of substitutability, which crops up again in Section 8.2, warrants a good deal of further research.

**Figure 4: A DEVELOPING COUNTRY MODEL,
TOTALLY DEPENDENT ON RENEWABLE RESOURCES**



Our conclusion here is that most single-valued sustainability criteria, including our chosen definition of non-declining utility, can be reduced to "maintaining the capital stock intact". However, this does not make choosing between them any easier. Deciding what is the relevant capital stock, and how it should be measured, inevitably boils down to deciding how essential to and substitutable in production are the different components of capital: machines, technical know-how, renewable and non-renewable resources.

The answers directly affect the operational relevance of a sustainability criterion. In a world of perfect certainty, a sustainability criterion which focuses on preserving just the natural capital stock will not make sense if man-made capital can always substitute for natural capital and is steadily being accumulated. Nor will it make sense to focus on a purely physical measure of the "effective resource base" (man-made plus natural capital) if technological progress is steadily increasing the economic value that can be produced from one physical unit of capital. The uncertainty of future technical progress may mean that a purely physical measure is prudent, but one must be aware that the answers given will be over-cautious. Finally, if sustainability is to mean anything for trading and manufacturing nations, it will not make sense to focus solely on a nation's own resource stocks; what will matter is maintaining balanced trade and the productivity of its physical and human capital, possibly in the face of rising real prices for resource inputs it needs to buy on world markets.

4. OPTIMAL CONTROL AND SUSTAINABILITY

4.1 The role of optimal control models

Returning now to the general model of Section 2, one would like to be able to analyse the various features of an optimal development path, depending upon the initial stocks in the economy, the various functional relationships in Section 2.3 for output Q , resource growth G , pollution assimilation A , population growth dN/dt , labour productivity L and social welfare U . What is the optimal depletion rate of non-renewable resources? What are the optimal stocks and flows of renewable resources? Does optimal pollution increase or decrease over time? Does optimal consumption increase or decrease? Above all, does optimal utility increase or decrease, that is, is optimal development sustainable or unsustainable? (Recall that "optimal" here means nothing more than the maximisation of discounted utility, as shown in Table 2.)

Unfortunately a general mathematical solution of such a complex system, using dynamic optimisation techniques such as optimal control theory, is quite impossible. We are then forced to use highly simplified models, with all the defects that were pointed out in Section 1.3. The alternative is simulation modelling, i.e. computing a solution using real data and estimated functional forms. This approach has value - for example, it can shed light on "catastrophes" (Ayres and Sandilya 1987) - but any results will lack generality and may give little theoretical insight.

Good summaries of what optimal control theory can achieve in the field of economic growth with natural resources and pollution are in Clark (1976), Smith (1977) and Kamien and Schwartz (1982). There are intrinsic mathematical problems in analysing systems with more than two endogenous "state variables", and even assuming away all the problems of aggregation, the model in Section 2 has five state variables: capital K , renewable resources S_a , non-renewable resources S_n , pollution P and population N . Kamien and Schwartz review models that include just K , S_n and P as endogenous variables, and thus ignore both population and renewable resources, or at least treat them as exogenously determined. They find that only one model (Maler 1974, Ch 3) attempts to cover all three variables, and then says little useful about the solution. The models that do cover renewable resources are typically partial equilibrium fishery or forestry models that take the price of the resource as given rather than endogenous. These cannot tell us much about the sustainability of poor economies that depend on renewable resources, although they may be useful for looking at trade in cash crops.

One important result for sustainability does spring out of the models that just look at capital K and non-renewable resources S_n , namely that the optimal solution often results in declining utility in the distant future, i.e. is not sustainable. This occurs in Dasgupta and Heal (1979, p299), Dixit (1976, p160), Kamien and Schwartz (1982, p61), and Lusky (1975, p325), to name but a few. The intuition is fairly obvious. If non-renewable resources are essential to output, consumption and utility, and if discounting reduces the perceived value of future utility, then in the absence of continuous technical progress which allows output per unit of resource input to rise without limit, declining utility is eventually inevitable as the resource runs out. If the resource input is also an environmental amenity (or if the resulting pollution is a disamenity), the decline of utility will be even worse. This is not always obvious in the literature, as authors (e.g. Lusky 1975) may not bother to compute the optimal utility path. Sections 6 and 7 give simple models of non-renewable resource depletion which illustrate these points. One result there is that high discount rates can cause the optimal utility path to be unsustainable: this is relevant in discussing the relationship between optimality and sustainability, to which we now turn.

4.2 Optimality and sustainability

We noted at the start of Section 3 that sustainability criteria are constraining, not maximising, criteria. Several different futures may be sustainable, and a sustainability criterion will not say which sustainable future is the best to pick. The obvious answer would be to pick the optimal sustainable future: that is, the sustainable development path which gives the greatest present discounted value. This notion, that sustainability constrains optimality rather than completely replacing it, is clearly spelt out in Goodland and Ledec (1987, quote 1), Pearce (quote 2), and Tietenberg (quote 2).

Yet it raises important philosophical questions about collective decision-making. A fully optimal solution will fully reflect the interests of the

current generation of decision makers: it will have corrected for all market failures such as pollution externalities (as we shall see in Section 7), distortions in interest rates caused by income tax, imperfect information, etcetera. Why then should the current generation seek to impose a sustainability constraint on its own decisions? If it is concerned that high discount rates will lead to profligate resource consumption now and hardship for future generations, why does it not lower its discount rate?

This is not an easy question. One answer could simply be that the "sustainability lobby" has a lower discount rate than the rest of society, and is seeking to impose its own world view (in which the optimal future is also sustainable) on the rest of society (which doesn't care about sustainability).

A more appealing answer is that people do not have a single set of preferences that apply to all decisions. Preferences for social goals may be separate from preferences for private behaviour (Solow 1974a, p9, p10 and Page, 1983 and 1988). It is possible to feel differently about a course of action according to whether one is listening to one's individually selfish desires or one's sense of social responsibility about the future; to behave one way in the market place and yet to vote for a government which has policy goals separate from just perfecting the market place by supplying of public goods and reducing public bads. This comes near what Marglin (1963a, p98) calls the "schizophrenic" answer: "The Economic Man and the Citizen are for all intents and purposes two different individuals." We would not go as far as this, since Economic Man can still maximise self-interest (seek optimality) within the bounds (sustainability) that the Citizen lays down.

A strong word of caution is necessary to balance the above remarks on private selfishness and public responsibility. There is a strong tendency in neoclassical welfare economics, based in part upon analyses of savings externalities such as in Sen (1967), that collective concern for the future, as expressed by government policies, is greater than private concern, as expressed by free market decisions. This is not necessarily so, as the public choice literature quite clearly shows. Given that governments do not simply maximise social welfare, they may use higher discount rates than private individuals, so that less rather than more government intervention will be what is needed to make economic development more sustainable. This countervailing theme is discussed in Section 7.2 below, and it should be borne in mind throughout this paper, even if it is not always explicitly stated.

Having completed our survey of concepts of growth, development and sustainability, we now apply them in Part II.

PART II: APPLICATIONS

5. ECONOMIC GROWTH AND THE ENVIRONMENT - BALANCING CONSUMPTION AND CLEAN-UP EXPENDITURE

This section is a slight digression from the main question of sustainability. It looks the related issue of when and why economic growth and environmental improvement may be mutually consistent objectives over time, even if they are antagonistic at any point in time. Our simple comparative static analysis seems hardly new, but in fact there is remarkably little literature on the way in which changes in economic growth affect the optimal of environmental quality. Most papers either ignore the fact that society can choose a level of environmental quality by varying its spending on pollution control ("clean-up"), or look only at long run steady states. The closest analysis to what follows seems to be the optimal control model in Forster (1973), but he does not address the issue of whether optimal environmental quality improves or declines as optimal growth proceeds.

First of all, assume that investment I is some fixed proportion of output Q , so that we ignore the problem of how to determine the optimal level of saving and capital accumulation. The analysis is comparative static, with output Q regarded as exogenously determined. We may as well then treat output as simply divided between consumption C , and clean-up expenditure X :

$$Q = C + X$$

The physical waste flows inevitably associated with output Q (whether used for consumption or clean-up) cause pollution and lower overall environmental quality E , but clean-up expenditure itself lowers pollution and raises environmental quality:

$$E = E(Q, X); \quad E_Q < 0, \quad E_X > 0$$

Note that there is no stock pollution effect here: environmental quality is purely determined by current flows of output and clean-up. The appropriate "stripped-down" version of Figure 1 for this economy is Figure 5. Therefore the change in environmental quality as output changes is

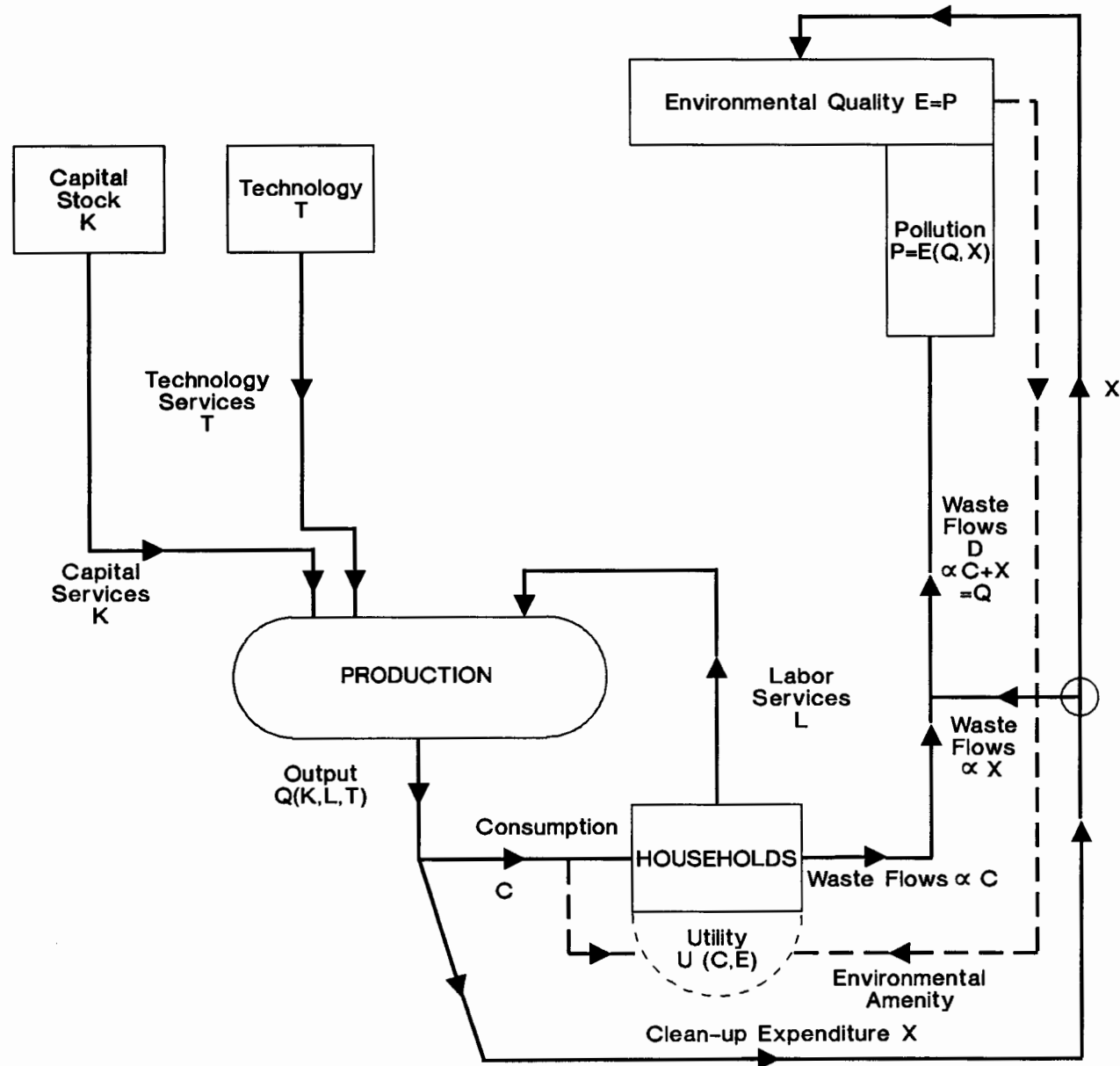
$$dE = E_Q dQ + E_X dX < (E_Q + E_X) dQ$$

The inequality is because we would not expect the increase in clean-up expenditure, dX , to be greater than the increase in total output, dQ . So:

$$(-E_Q) > E_X \rightarrow dE/dQ < 0$$

This says that if increased output dQ generates more pollution than can be cleaned up by spending all of the increased output on clean-up, then economic growth will inevitably cause environmental degradation. It is important to state this to counteract the simplistic view still often expressed that "we must grow in order to clean up the effects of growth"; clearly this is not always true even physically, let alone economically when there is a choice

**Figure 5: ECONOMIC GROWTH AND THE ENVIRONMENT:
A STATIC MODEL WITH CLEAN-UP EXPENDITURE**



between spending on consumption and spending on clean-up. Everything depends upon the type of growth and how much extra pollution it causes.

A more interesting question is how the optimal, rather than technically possible, level of environmental quality changes as output grows. The choice between consumption C and clean-up expenditure X is determined by choosing X (and hence $C = Q - X$) to maximise social welfare

$$U[C, E] = U[Q-X, E(Q,X)]$$

The first order condition for maximisation is

$$-\partial U/\partial C + (\partial U/\partial E)(\partial E/\partial X) = 0$$

From this equation (checking that it does maximise rather than minimise welfare), one can in principle calculate the optimal clean-up expenditure and optimal environmental quality as functions of the given level of output:

$$X^* = X^*(Q), \quad E^* = E^*(Q)$$

and the interesting question is then whether $dE^*/dQ > 0$ or < 0 : that is, does environmental quality optimally improve or decline as the economy grows?

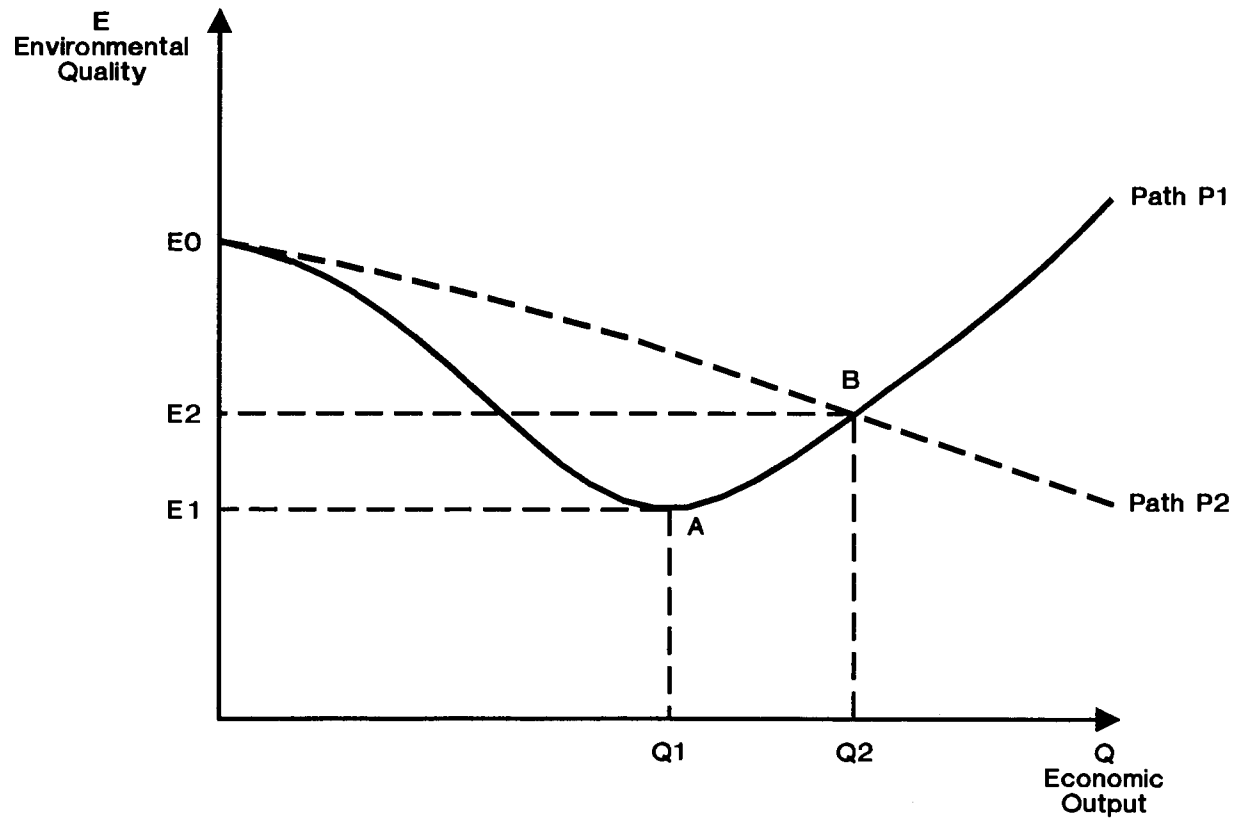
It is impossible to answer this in theory: everything depends upon the functional forms $U(\cdot)$ and $E(\cdot)$, and neither of these are easy to measure in practice! However, making heroic assumptions about how aggregate environmental quality should be measured, casual empiricism suggests that most industrialised countries seem to have grown along something like the path P_1 in Figure 6, certainly with regard to local air and water pollution. Environmental quality starts off at a pre-industrial level E_0 ; declines to a minimum E_1 at the height of resource-intensive industrialisation; then recovers to E_2 at point B, representing the present position of a mature industrial country where output has grown to Q_2 .

Is such a typical path optimal? It is not hard to suggest reasons why it may be. In the early phases of growth, people are poor and are willing to trade off decreases in environmental quality for significant improvements in material consumption. But then as they grow richer and the environment gets worse, their relative valuation of consumption and environmental goods alters and they spend an ever greater proportion of output on cleanup X rather than on consumption C , leading to the turn-around in environmental quality beyond point A as shown.

Under this hypothesis, economic growth and environmental improvement are indeed compatible in the later stages of growth, and much of the new conventional wisdom on growth and the environment holds that they will continue to be compatible in the future, as shown by the upward slope of path P_1 beyond output Q_2 . The message for developing countries would then be that poor environmental quality is just a necessary phase to pass through on the optimal road to mature development.

However, this does not mean that developing countries can ignore the need for

**Figure 6: POSSIBLE TRADE-OFFS BETWEEN OUTPUT AND ENVIRONMENTAL QUALITY
(AS OUTPUT Q GROWS OVER TIME)**



environmental policies. The fact that they often do gives rise to an alternative, much gloomier hypothesis. This states that environmental policy is inevitably weak in the early stages of industrialisation, because the environment has not been polluted before, so no "modern" property rights over it exist.³ Property rights take many years to establish through the political process, and in the meantime growth follows a path of intensive resource use, causing excessive pollution and leading the economy to point A. Only when environmental property rights and an active environmental policy are established, will sufficient output be diverted to cleaning up pollution so that environmental quality can recover to its present level E2 at point B.

The true optimal path, if environmental property rights had been defined and enforced from the start, might be path P2 passing through B (or it might first rise and then fall - see Pearce et al 1988, pl8). Along this path environmental quality steadily declines, and the rosy future promised by path P1 is simply unattainable: the environment's assimilative capacity and the returns to further clean-up expenditure are reaching some ultimate limits (see Section 8.2). In a dynamic sense it may then not be desirable to proceed down path P2, and economic growth ideally comes to a halt and (if we are lucky and avoid continual environmental deterioration from cumulative pollution) a steady state is reached. Under this hypothesis, environmental improvement and economic growth are only consistent in the real world during the "catching-up" phase from A to B when environmental externalities are being internalised.

6. NON-RENEWABLE RESOURCES I: SUSTAINABILITY AND THE DISCOUNT RATE

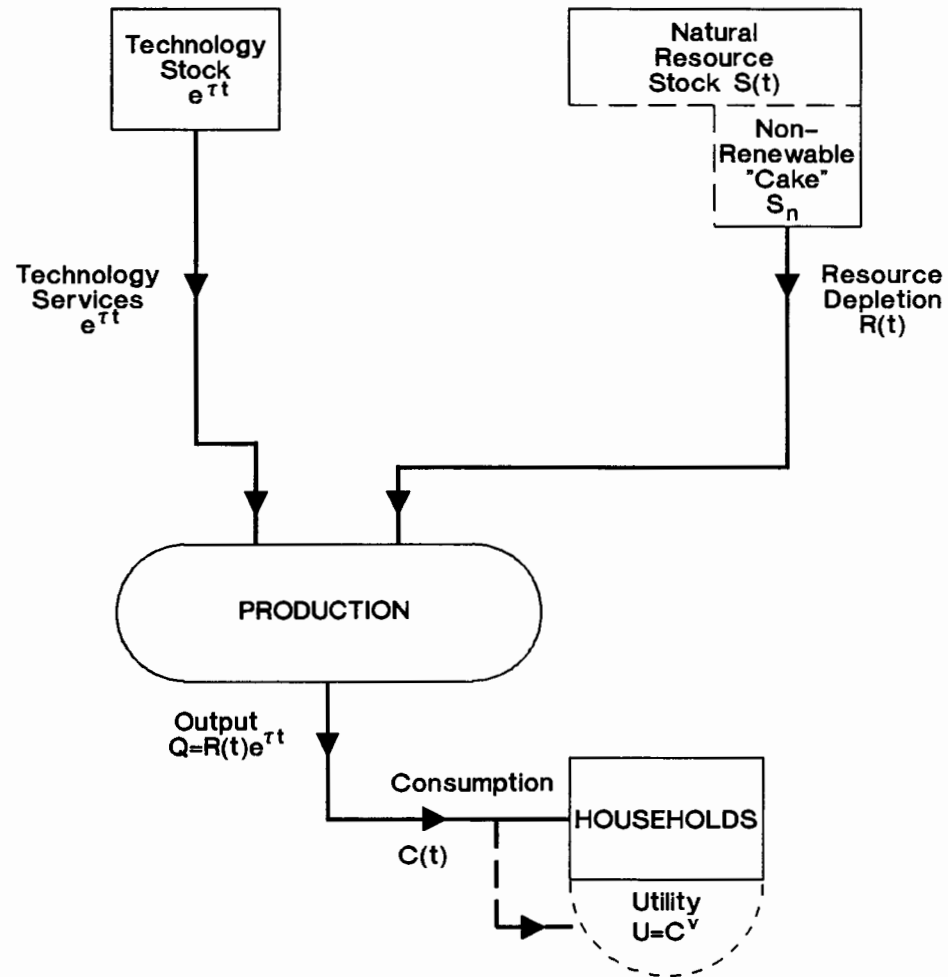
This and the following three sections make use of optimal control models of resource depletion over time. Only the key formulae and results are presented here, and discussed in an intuitive way; for further mathematical detail the reader is referred to Appendices 2-5, which correspond to Sections 6-9 respectively. Sections 6-8 deal with non-renewable resources and thus are mainly of interest for industrial countries; Section 9 deals with renewable resources and is of interest for a poor agrarian country.

The model in Appendix 2 is one of pure "cake-eating". The economy simply processes some non-renewable resource stock $s(t)$ into a consumption flow $c(t)$ as follows (s , c , u are all per capita quantities respectively equal to S/N , C/N , and U/N):

$$c = -\dot{s}e^{rt}; \quad \text{initial resource stock } s(0) = s_0$$

³ A more careful analysis might show that property rights over the environment did exist before industrialisation did exist, but in the traditional, common property form practised by peasants or indigenous tribespeople. The advent of Western concepts of capitalist development and "modern" (that is, private and legalised) property rights may break down such communal systems of restraint. This paradoxically leads to no property rights at all, and hence severe environmental degradation, in "frontier economies". See for example Southgate and Runge (1985).

Figure 7: A CAKE-EATING MODEL WITH NO ENVIRONMENTAL EFFECTS



Any other inputs (capital, labour, renewable resources) that are required for this process are assumed not to be scarce, and are ignored; **Figure 7** gives the reduced form of **Figure 1** to which this model corresponds. As time proceeds, the cake-processing becomes steadily more efficient because of exogenous technical progress at a constant exponential rate τ . Consumption yields utility, but the marginal utility of consumption diminishes:

$$u(c) = c^\nu, \quad 0 < \nu < 1.$$

Clearly assumptions that allow the ratio of consumption output to cake input to increase without bound, and without any resources devoted to advancing technical progress (thus abandoning the assumption in Section 2 that technology is a produced input like physical capital), are highly questionable, and are discussed further in Section 8.2. For the moment we are interested in the results of the above assumptions.

Appendix 2 shows that the optimal solution of the simple cake-eating model is a steadily declining rate of resource depletion, which may however (depending on the rate of steady technical progress in resource processing) be converted into increasing consumption, and hence increasing utility, over time:

$$c^*(t) = \phi s_0 e^{(\tau-\phi)t}, \quad u^*(t) \propto e^{(\tau-\phi)\nu t};$$

$$\text{where } \phi = (\delta - \tau\nu)/(1-\nu) \quad \text{and hence} \quad (\tau - \phi) = (\tau - \delta)/(1-\nu)$$

In this model Turner's remark (1988, quote 4) about sustainable use of a non-renewable resource does not apply: resource depletion is always positive, but sums to a finite number just like the series $1 + 0.1 + 0.01 + 0.001 + \dots$. The condition for sustainability is that the rate of technical progress τ exceeds the rate of utility discounting δ . So if δ is high enough - that is, if the current generation's valuation of the future is low enough - then a future that is steadily impoverished is optimal. The higher δ is, the higher the initial consumption $c^*(0)$ and the faster it declines.

In such a circumstance the government intervention can create incentives for resource conservation that will achieve sustainability, and such incentives are analysed in Section 7 below. Conversely, it is possible that private actions would result in sustainability, but the government may already be subsidising resource depletion. If so, removing the government intervention will restore sustainability.

The model can easily be interpreted in terms of the rate of return on investment. Investment is simply abstention from resource depletion; the return to investment is the increased value of the resource over time thanks to technical progress at rate τ . A high τ , meaning a high interest rate, is beneficial to resource conservation. Thus high interest rates do not necessarily harm conservation, a theme to which we return in Section 8.

7. NON-RENEWABLE RESOURCES II: SUSTAINABILITY AND ENVIRONMENTAL DEPENDENCE COMBINED.

7.1 The model - cake-eating with environmental amenity or productivity

Appendix 3 sets out the details of an extended cake-eating model, which differs from the model in Appendix 2 in two ways. Firstly, the economy explicitly comprises N non-cooperating but economically identical people, with the total resource stock $S = Ns$ where s is the per capita resource stock. Secondly, the total resource stock is also assumed to be the "environment", and has either an environmental amenity effect on utility:

$$u = u(c, S) = c^\nu S^\epsilon; \quad 0 < \nu < 1; \quad 0 < \epsilon < 1 \text{ measures environmental amenity}$$

as depicted in Figure 8, or an environmental productivity effect on consumption, as depicted in Figure 9:

$$c = c(\dot{s}, S) = -\dot{s} S^{\epsilon/\nu} e^{\tau t}; \quad \epsilon > 0 \text{ measures environmental productivity}$$

The idea of environmental amenity goes back at least to Vousden (1973); the idea of associating environmental quality with the level of unextracted resource is found in Kamien and Schwartz (1982); and the two are combined in Krautkraemer (1985). What is new here is the effect of non-cooperation: in both the amenity and productivity cases, people ignore the environmental value of the resource when planning their privately optimal path. With these particular, multiplicative functional forms, there is no difference in the privately optimal paths of resource depletion or utility between the amenity and productivity cases. The results are, with the cooperative (socially optimal) results give for comparison:

Non-cooperation (private optimum)

$$s^*(t) = s_0 e^{-\psi t} \quad \text{where } \psi = (\delta - \tau\nu)/(1 - \nu - \epsilon) > \phi \text{ in Section 6}$$

$$\dot{u}^*/u^* = \nu(\tau - \delta(1 + \epsilon/\nu))/(1 - \nu - \epsilon)$$

Cooperation (social optimum)

$$s^*(t) = s_0 e^{-\theta t} \quad \text{where } \theta = \nu(\delta - \tau\nu)/[(1 - \nu)(\nu + \epsilon)] < \phi \text{ in Section 6}$$

$$\dot{u}^*/u^* = \nu(\tau - \delta)/(1 - \nu)$$

Thus resources are depleted faster and sustainability ($\dot{u}^*/u^* \geq 0$) is harder to achieve than in purely materialistic model of Section 6, because of the environmental effect ϵ .

There are three policy cases here, illustrated in Figure 10, with Case A of Appendix 2 now split into two sub-cases. (We expect this threefold classification to apply to many "tragedies of the commons" cases where externalities and non-cooperative behaviour lead to a nonoptimal profile of resource depletion.)

Figure 8: A CAKE-EATING MODEL WITH ENVIRONMENTAL AMENITY

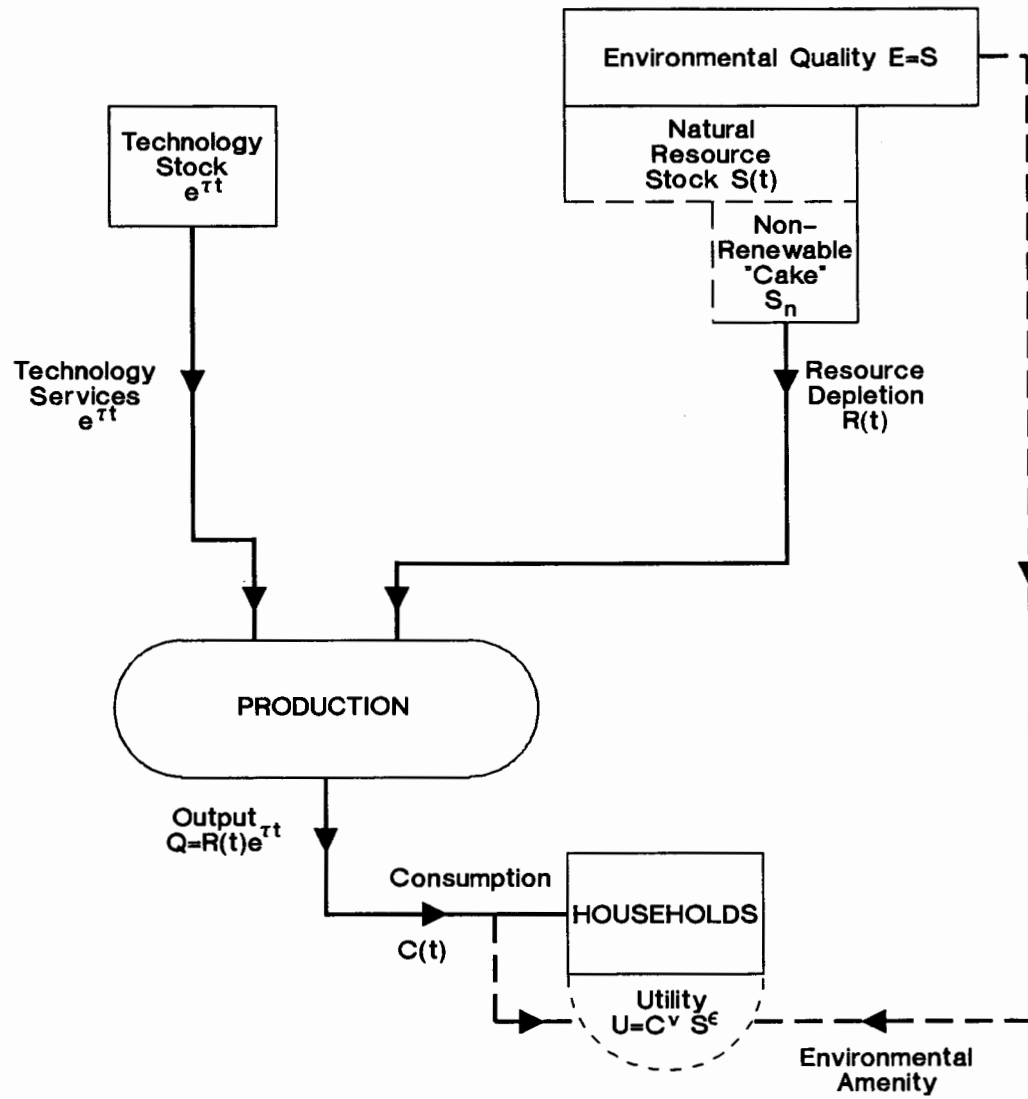
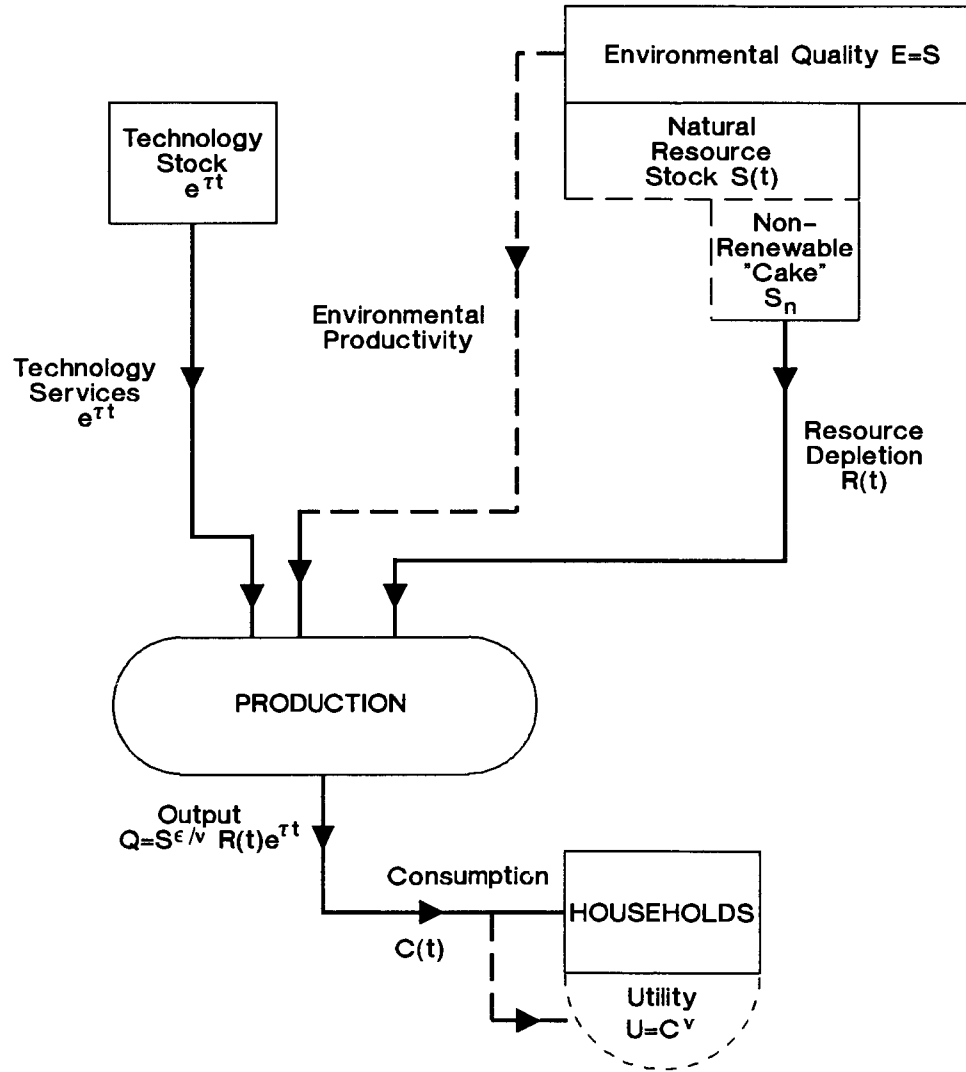


Figure 9: A CAKE-EATING MODEL WITH ENVIRONMENTAL PRODUCTIVITY



ksr/w43953l

- A1 If $\delta \leq \tau/(1+\epsilon/\nu)$, the non-cooperative path is nonoptimal but has $\dot{u} \geq 0$, i.e. is "sustainable". In this case optimality requires some government policy intervention to conserve resources more. Sustainability alone requires no intervention, even if the government ignores the nonoptimality. Note that sustainability implies no criticism of a positive utility discount rate ($\delta > 0$) per se.
- A2 If $\tau/(1+\epsilon/\nu) < \delta \leq \tau$, the non-cooperative path is both nonoptimal and has $\dot{u} < 0$, i.e. is unsustainable, while the socially optimal path is sustainable. Optimality again requires government policy intervention to conserve resources. Such optimal intervention will at the same time make the economy sustainable.
- B If $\delta > \tau$, both the non-cooperative and socially optimal paths have $\dot{u} < 0$, i.e. are unsustainable. In this case resource conservation policies which achieve the social optimum are not enough to achieve sustainability. Sustainability requires a stronger intervention policy, the strength of which can be justified only by a moral commitment to intergenerational equity.

Appendix 3 shows how the government can alter the rate of resource depletion in the economy by offering conservation incentives: either proportional resource conservation subsidies σ , or declining depletion taxes. According to the strength of σ , any desired resource depletion rate (and hence utility growth rate in Figure 10) can be achieved. Also all these results are shown to have a direct interpretation in terms of "maintaining the effective resource base" of the economy, an alternative approach to sustainability introduced in Section 3.6.

7.2 Relevance to policy - can environmental policy help sustainability?

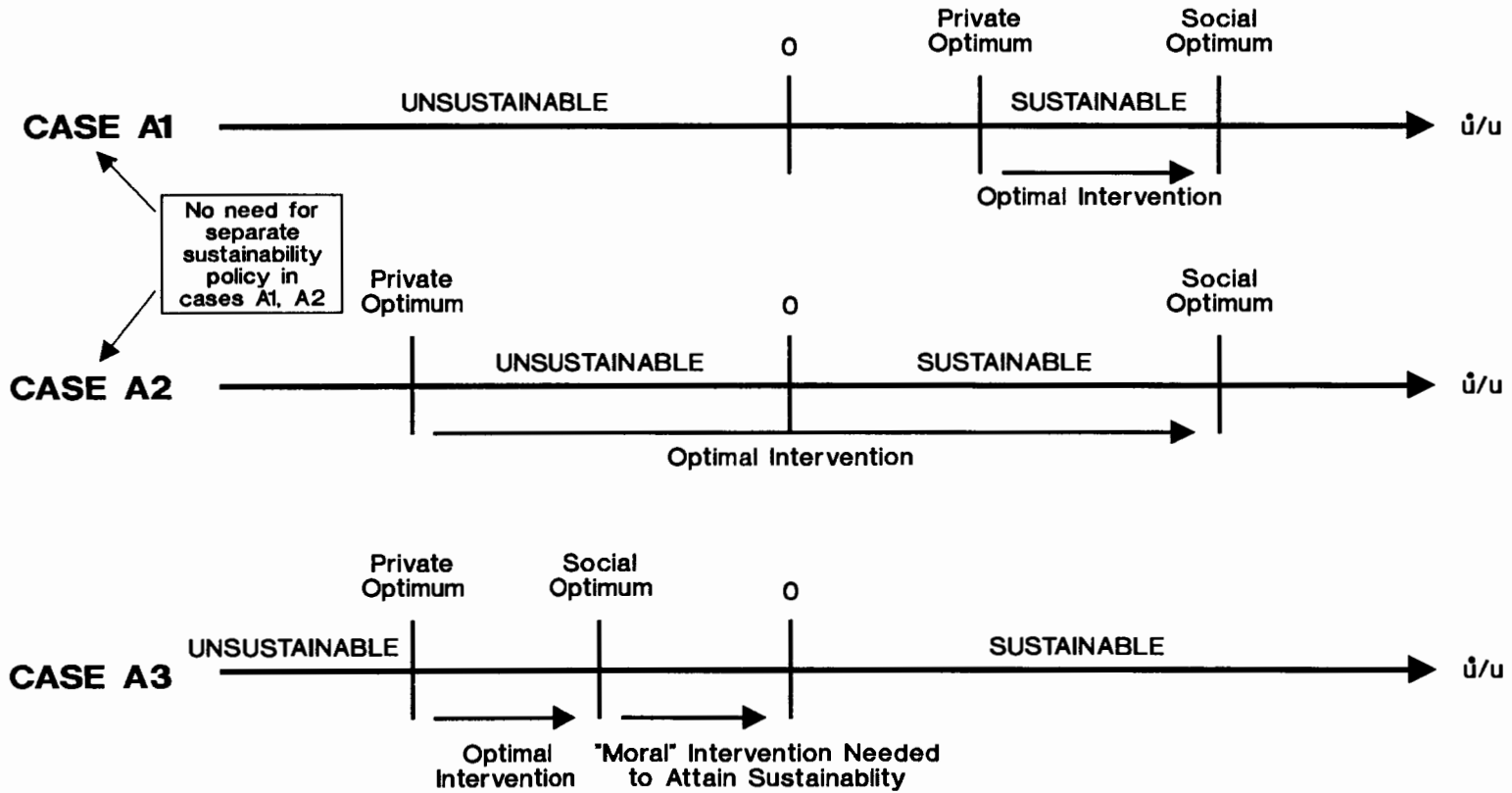
The above model gives a simple example of how environmental protection and economic welfare can be compatible in the long term. In an economy that is totally reliant on natural resources for economic output, and where the resource itself has environmental value, "environmental protection" (reducing the rate of natural resource depletion) is essential for "sustained economic growth", i.e. positive growth of consumption and utility into the indefinite future. Resource conservation incentives can make the economy more sustainable (i.e. move us to the right on Figure 10).

Conversely, resource depletion incentives can make the economy more unsustainable. As noted at the end of Section 4.2, many governments implicitly use high discount rates and promote policies which amount to incentives for resource depletion. Page (1977) highlighted the role of depletion allowances for non-renewable resource extraction in the U.S. The World Bank (1987) and Repetto (1988b) emphasise how resource extraction in developing countries is often heavily subsidised, although many of these are renewable resources to which our model cannot directly apply. The World Resources Institute has done sterling work in cataloguing examples of such subsidies in developing countries (Repetto 1985b, 1986b, 1988a). So the emphasis for both environmental and sustainability policy in such circumstances must be to reduce government intervention, not increase it.

Figure 10: SUSTAINABILITY, OPTIMALITY AND GOVERNMENT INTERVENTION

Optimal $u^*(t)$: maximizes $\int_0^{\infty} u(t)e^{-\delta t} dt$

Sustainable $u(t)$: has $\dot{u} \geq 0 \forall t > 0$



* In all cases, "choosing" a higher discount rate δ moves the optimum towards unsustainability *

The suggestions of the above analysis for sustainability policy - they can only be suggestions, because the model is so very simple - are as follows. If natural resource use is socially excessive (as judged by conventional optimality criteria which take all environmental spillover effects into account), a separate sustainability criterion may simply be redundant in many practical cases. Removing depletion incentives, and replacing them where necessary by conservation incentives, will usually improve sustainability as an automatic side-effect (Case A2 in Figure 10). These conclusions also emerge strongly from the numerous empirical studies by Repetto cited above. Given that it will be much easier to sell such policy changes by appealing to the collective self-interest of the current generation, rather than to noble concepts of intergenerational justice, there is much to be said for concentrating practical efforts on strengthening conventional environmental policies.

However, one must also point out the differences between long-run optimality and short-run output maximisation in the model of Appendix 3. In all cases, a higher steady growth rate of consumption and utility is achieved only by lowering the initial levels of consumption and utility, as illustrated in Figure 11. In the real world this means negative economic growth in the short term, which will impose heavy transitional costs on an economy (costs which are not included in our model) and thus tough political choices, even though the outcome may be optimal in the long term. Thus our model provides a crude explanation of the observation by the World Bank (1987, quote 4) that

"Promoting growth, alleviating poverty, and protecting the environment are mutually supportive objectives in the long run. ... In the short run, however, the objectives are not always compatible..."

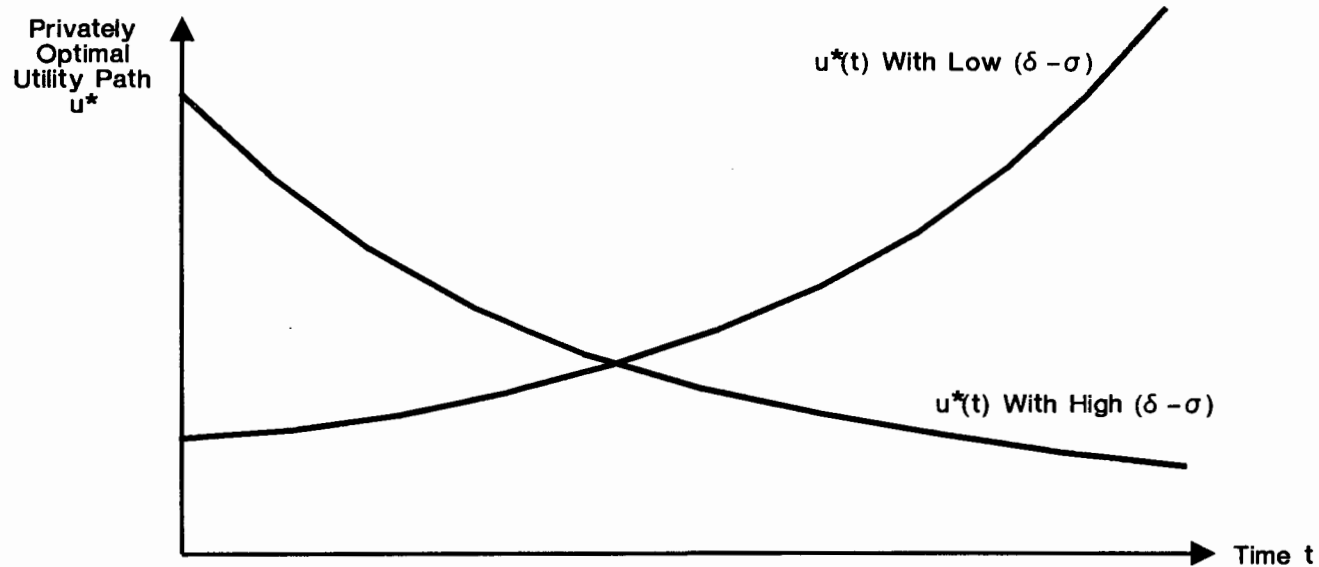
7.3 Property rights and environmental policy

Section 7.2 pointed out the importance of conventional environmental policy in improving the sustainability of development paths. Environmental policy is all about internalising externalities; and internalising externalities usually amounts to establishing some kind of property rights over the environment. Instead of air, water etc. being open access resources, they have to be owned by someone. Here we briefly review the problems that can arise in determining the distribution of own environmental property rights.

In the ideal case of symmetric congestion externalities, such as analysed in Section 7.1, no distribution problem arises. Everyone both contributes equally to, and suffers equally from, the social problem of excessive resource degradation. Under the proposed solution (government conservation incentives), everyone contributes equally to the solution and no equity problems arise.

Environmental problems are rarely symmetric in the real world. Often one can separate the polluter from the pollutee, and the question then arises as to who should own the environmental property right. Should the factory own the river, and charge local citizens for swimming and fishing in it? Or should the community own the river, and charge the factory for discharging its

Figure 11: EFFECT OF A LOWER EFFECTIVE DISCOUNT RATE ON INITIAL UTILITY



In the cake-eating models of Section 7, the non-cooperative (privately optimal) path of utility is

$$u^*(t) = \left(\frac{\delta - \sigma - \tau v}{1 - v - \epsilon} \right)^v S_0^{v+\epsilon} \exp \left\{ \frac{\tau v - (\delta - \sigma)(v + \epsilon)}{1 - v - \epsilon} t \right\}$$

Therefore a lowering of the effective discount rate $(\delta - \sigma)$ – whether by consumers choosing a lower utility discount rate δ or by the government raising the conservation subsidy σ – will improve sustainability (raise \dot{u}^*/u^*), but will also lower the initial level of utility $u^*(0)$.

effluent into it? There are two main schools of thought on this. One school, started by Coase (1960), holds that efficient resource allocation may be achieved irrespective of whether pollutee or polluter has right to use the environment. The sole role for government is in defining and enforcing property rights. The conditions for this "Coase theorem" to hold are very restrictive: all users of the environment must have perfect information, bargaining between them must be costless, and changing environmental property rights should cause no significant income effects. Nevertheless, the Coase perspective is important, particularly in contrast to the other school which assumes that internalising externalities means that the "polluter must pay", for example through emission charges. This view dates back to Pigou (1932), was boosted by the declaration of the Polluter Pays Principle (OECD 1972) and is still widespread (e.g World Bank 1987, p23).

An amalgam of the two views is that while government environmental policies (beyond merely defining property rights) are necessary to overcome the problems of imperfect information and transaction costs, it will often be counterproductive for such policies to make the polluter pay. De facto pollution rights often exist within the political system, and policies such as emission charges may radically change pollution rights and thus be politically unacceptable. More progress may therefore be made towards efficient and sustainable use of environmental resources if other policies are pursued (such as a charging/subsidy mix) which internalise environmental costs without challenging pollution rights (Pezzey 1988).

This is not to say that environmental property rights should never be changed. The discussion in Section 10, about the income and hence allocative effects of redistributing environmental property rights from rich to poor people, shows that such redistribution might be an effective way of simultaneously improving the lot of the poor and improving the environment. But the political difficulties of such redistribution should never be underestimated, since they will certainly limit the pace at which redistribution can proceed.

Finally, one must question whether the property rights approach can be a universal solution to environmental problems. Can one really extend the notion of ownership to global resources such as the stratosphere and the oceans? The costs of excluding non-owners from using these resources suggests that this may be impossible, and alternative mechanisms may be needed. Now for thousands of years indigenous peoples have managed many common property (as opposed to open access) resources on a small scale in a sustainable way, using non-legal and non-economic mechanisms such as consensus, cooperation and tradition, as well as private rights (Southgate and Runge 1985, Runge 1986). The ultimate challenge for the human species may therefore be to rediscover and reapply these common property mechanisms on a global scale.

8. NON-RENEWABLE RESOURCES III: THE ROLE OF INVESTMENT, AND TECHNOLOGICAL LIMITS TO GROWTH

8.1 The model - capital growth with environmental amenity or productivity

Sections 6 and 7 ignored the role of capital (K) in economic growth and

resource depletion. Clearly capital can substitute for resources in many ways: using a clock thermostat to reduce energy consumption for space heating is a simple example. Appendix 4 sets out the bare details of a simple model that allows capital investment or accumulation, using a Cobb-Douglas production function for output. As in the Section 7/Appendix 2 model we regard the total resource stock S also having the properties of a public environmental good. We introduce either multiplicative environmental amenity (strength ε) into the utility function, or multiplicative environmental productivity (strength π) into the production function, as follows (L = labour, R = resource flow, τ = technical progress):

Environmental amenity

$$\text{Utility } u = c^\nu S^\varepsilon \quad \text{Output } Q = AK^\alpha L^\beta R^\gamma e^{\tau t}$$

Environmental productivity

$$\text{Utility } u = c^\nu \quad \text{Output } Q = AK^\alpha L^\beta R^\gamma S^\pi e^{\tau t}$$

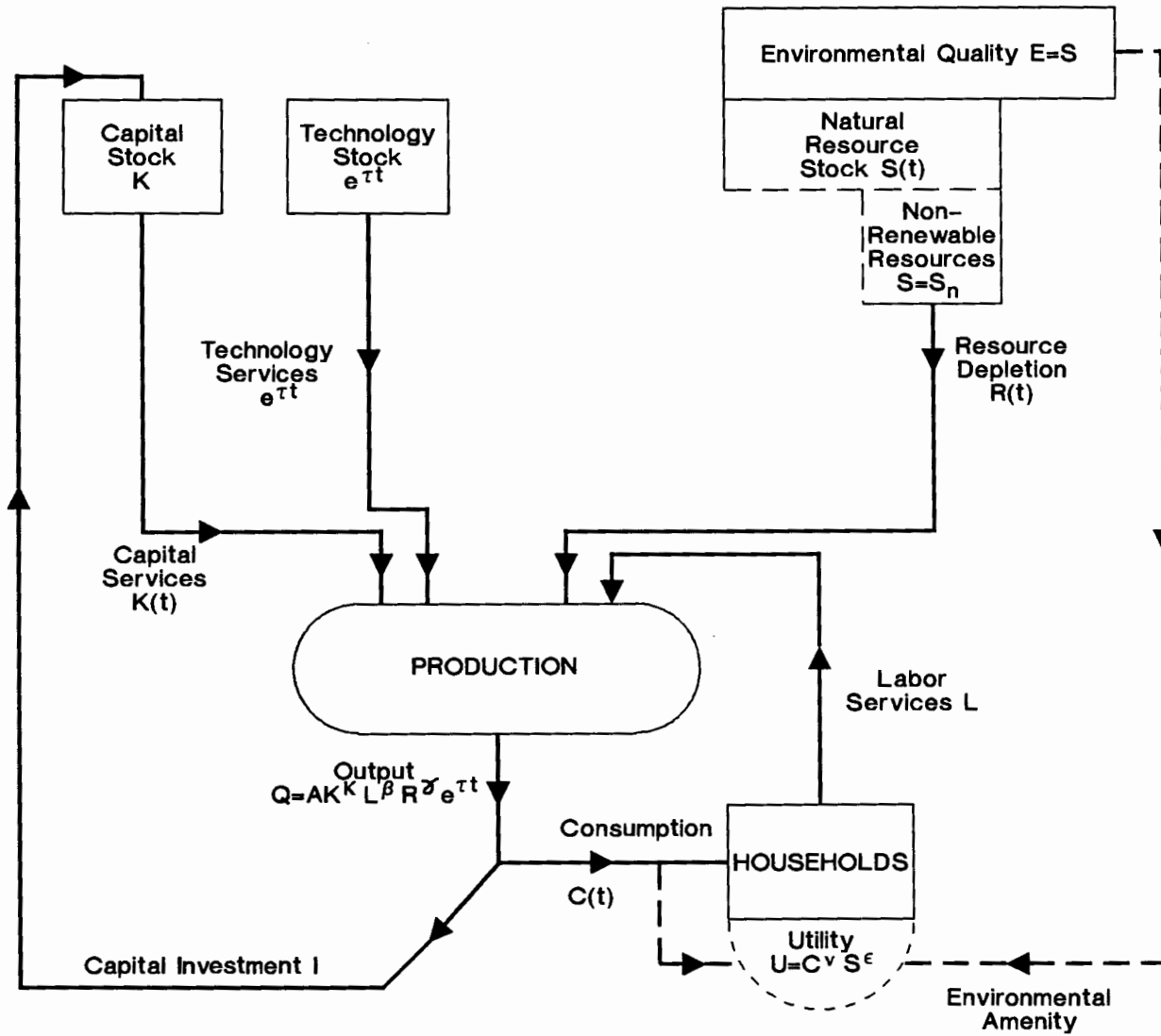
The environmental amenity model is illustrated in Figure 12. For such systems we cannot calculate the exact optimal growth path for resource depletion and capital accumulation starting from any given initial stocks of resources and capital. The most we can analyse is the optimal steady state when all stocks and flows are growing (or declining) exponentially. Appendix 4 gives the privately optimal resource depletion rate, real interest rate (= return on capital investment) and utility growth rate for each system, assuming again that the economy consists of non-cooperating agents who ignore the environmental cost of private resource depletion. The important things to note about the privately optimal solutions are that:

- o the resource depletion rate ($-\dot{S}/S$) rises as the environmental parameter (ε or π) rises;
- o the interest rate rises in the amenity case as ε rises, but falls in the productivity case as π rises;
- o the growth rate of utility falls as ε or π rises, and a higher ε or π raises the minimum technical progress τ needed to ensure sustainability.

Further analysis then shows that a proportional conservation subsidy σ (subject again to certain restrictions on parameter values) can move the economy onto an optimal growth path by countering all the depletion and utility effects: a higher σ will slow resource depletion and raise the growth of utility (i.e. improve sustainability). The case of resource depletion taxes has not been analysed here.

The suggestions (again, no general proof emerges from such a specialised model) for policy intervention to improve sustainability, are thus the same as in the "cake-eating" model of Section 7. The effects of conservation subsidies on reducing resource depletion and improving sustainability are in line with intuition, but the result that conservation incentives lead to higher interest rates warrants some discussion, which now follows.

Figure 12: A CAPITAL ACCUMULATION MODEL WITH ENVIRONMENTAL AMENITY



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8.2 Capital-resource substitution, interest rates and technological limits

The reason why higher interest rates are consistent with resource conservation in the above model is because capital and resources are substitutes in the Cobb-Douglas production function, so capital investment saves resources. If the effective value to the investor of resources saved is raised by implementing a conservation subsidy, then the return on investment, i.e. the rate of interest, will also be raised.

However, it may not always be the case that cost-minimising production decisions result in capital and resources being substitutes. It is easy to think of examples where labour-saving capital equipment (e.g. a bulldozer) also requires resources (i.e. diesel fuel) in order to be productive, although it is harder to model such capital-resource complementarity mathematically. We call the two types of investment **resource-saving investment** and **resource-using investment**, and the distinction proves to be important in our discussion of discount rates in Section 11.

The optimistic conclusion of the model in Section 8.1 is that, given high enough technological progress (and suitable resource conservation policies if environmental effects are important), sustainable development is possible with per capita output, consumption and social welfare growing without limits. Many dismiss such a future as physically impossible (e.g. Daly 1987), and it is important to note briefly why this may be so. An unconvincing argument is that ever-growing output must necessarily run out of material inputs and create ecologically unsustainable pollution loads. This is unconvincing because the throughput of material resources required to produce a unit of valued output might decline. Note that output is measured here in value, not physical units. The reduction in the energy/GNP ratio for the U.S. economy in the 1970s is an example of how high resource prices can induce substitution away from resource inputs; further reductions in the material intensity per dollar of output are clearly possible with continued capital accumulation and technical progress.

The important question concerns the ultimate limits of capital-resource substitution and technical progress. The laws of thermodynamics suggest that there must ultimately be a minimum requirement for resource inputs per unit of valued output and also per unit of man-made capital. Physical capital depreciates and requires material resource inputs to maintain it. Furthermore, natural resources, particularly biological resources, is vitally different from man-made capital in a number of ways (Pearce, Barbier and Markandya 1988) and so may be substitutable only up to some limit. Being part of a living ecosystem, biological resources are inherently multifunctional, are subject to irreversible and possibly catastrophic changes if stressed beyond certain thresholds, and they directly support life. However it is very hard to say what the limits of substitution might be, and whether they must ultimately reduce welfare levels (i.e. lead to unsustainability) in the distant future, or at least bring growth to an end (i.e. level off in a steady state).

Also it is important to realise that technical progress is not a free good but

itself requires scarce resources to be produced and communicated (Ayres and Miller 1980). It gives rise to external adjustment costs, borne by society as a whole. The role of education may turn out to be crucial, as longer and longer periods of education (consuming material resources) become necessary, both to learn and apply existing technologies, and to continually discover new ones. Technological limits to growth form a hugely complex subject area which we cannot consider further here. The limits to growth debate that was started by Meadows et al (1972) no longer catches the public eye, but it is still actively pursued (Smith 1979, Lehman 1981, Gibbons 1984, Baumol 1986, Nordhaus 1986, Perrings 1987 and Ayres 1988a, are just a few of the many contributions in the last decade).

9. RENEWABLE RESOURCES: POVERTY, SURVIVAL AND OUTSIDE ASSISTANCE

9.1 The model - corn-eating and subsistence consumption

In this section we consider a simple "corn-eating" model which tackles the most elementary questions of sustainability in a poor economy, where population is growing, and where output (essentially food supply) is entirely dependent on a single renewable resource, "corn". Consumption per capita c is close to some subsistence minimum c_m , reflected in a per capita utility function $u = (c - c_m)^\nu$. The model, analysed in Appendix 5 and illustrated in Figure 13, excludes any role for inputs of capital, labour, non-renewable resources or technical progress in the production process, and assumes that there is no environmental amenity effect on utility. The rationale for these assumptions would be that per capita consumption and resource stock levels are so low that concern for environmental quality per se is negligible, and people have neither the time, energy or education to bring about any technical progress in the corn-growing and harvesting processes. So the model very crudely illustrates some key policy choices for subsistence farming in the developing world.

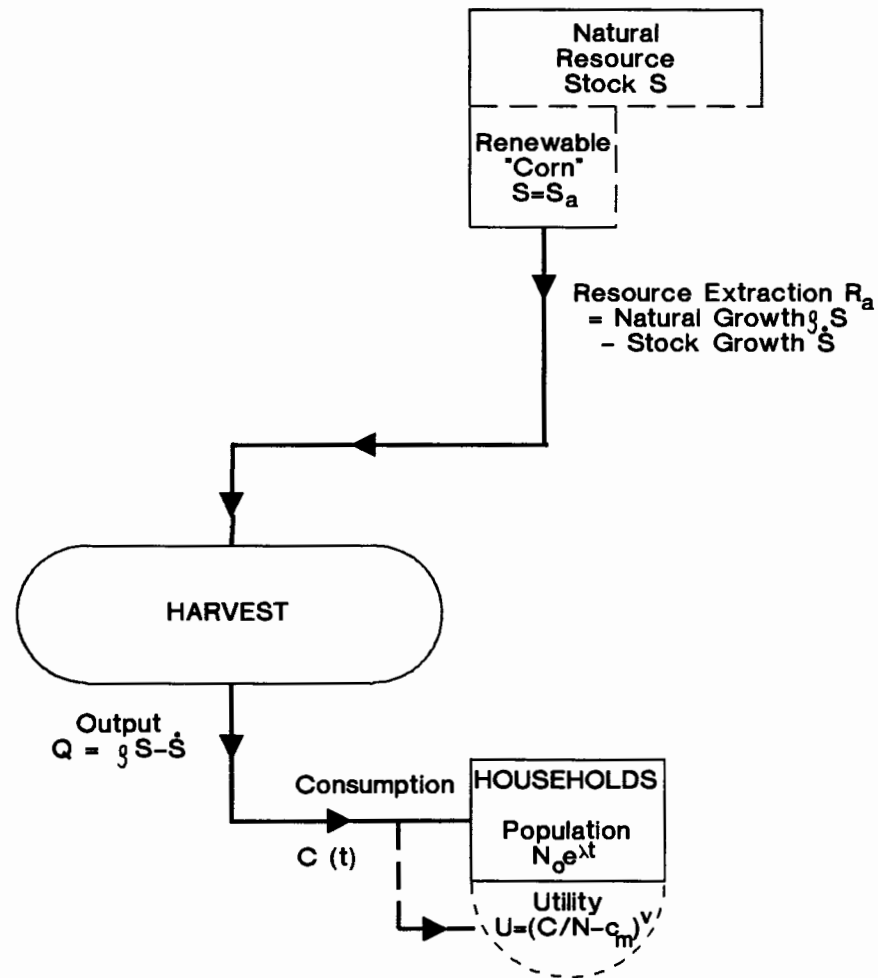
The model does not involve any common property environmental problems leading to nonoptimality, although it could be extended to do so by making the natural resource stock an open access rather than a privately owned resource.

Assuming that decision makers give no weight to future population growth when discounting utility, the model results are that per capita consumption c (and therefore utility u) can grow sustainably provided that both:

- (1) the resource growth potential ρ exceeds the sum of the utility discount rate δ and the population growth rate λ : $\rho > \delta + \lambda$. If not, then the consumption level declines exponentially to c_m and the society grinds along at subsistence levels for ever.
- (2) the minimum subsistence level of per capita consumption c_m is less than the per capita productivity of the initial resource stock s_0 , allowing for population growth: $c_m < s_0(\rho - \lambda)$.

If decision makers do give weight to future population growth when discounting

Figure 13: A CORN-EATING MODEL WITH SUBSISTENCE CONSUMPTION



utility, which would seem a fairer criterion in this model where population growth is exogenous, then the sustainability criterion (1) becomes $\rho > \delta$. This is easier to achieve and the growth of per capita consumption is slowed, because people are making conscious provision for extra mouths to feed in the future. However, the weighted utility criterion is questionable philosophically, since population growth is rarely exogenous in practice, and using a weighted criterion effectively treats future population growth as a good thing (Koopmans 1977). Note how a zero discount rate $\delta = 0$ is quite unrelated to sustainability here, as in the previous models with non-renewable resources (see for example Section 7.1).

The condition (2) is an initial condition to enable "take-off" into sustainable growth. If the harvest from the initial resource stock is not big enough, people will be forced to eat what should be set aside as seedcorn simply in order to survive the present, and this leads to inevitable disaster.

Crude implications for policy are that for an unsustainable economy to be converted into a sustainable one, one or all of the following must happen:

- o Increase the resource growth rate ρ ("improve the efficiency of farming");
- o Decrease the population growth rate λ ("promote family planning");
- o Increase the initial resource stock S_0 ("seek development aid");
- o Decrease the initial population N_0 ("famine and starvation").

Governments of very poor countries may not be able to implement the first three policies without outside assistance, hence the case for development aid from rich countries; otherwise the fourth grim solution will impose itself.

We can see here why the predominant concerns of survival here lead to a sustainability concept based on physical resource conservation rather than improving social welfare (see Sections 3.4 and 3.5 above). In a more realistic model with several different resources, resource accounting techniques would be important for measuring different resource stocks and growth rates, and for calculating meaningful aggregates (Repetto and Magrath, 1988, Ahmad et al, forthcoming).

9.2 Possible extensions

The shortcomings of the simple corn-eating model are many. There is no endogenous determination of population growth. There is no consideration of limitations that the carrying capacity of the environment would impose on resource growth, limitations that would often be modelled using a logistic growth function

$$\dot{S} = \rho S(S^C - S) \text{ where } S^C \text{ is the carrying capacity of the environment.}$$

Less renewable resources such as soil quality are also vitally important. Morey (1985) has an interesting model that assumes a constant absolute (as

opposed to the proportional increase above) in soil quality, and he studies the conditions required for total depletion of soil quality (i.e. desertification) to be optimal. However his is a partial equilibrium model that takes the value of output from the soil (i.e food) as exogenously given; he suggests endogenising food value by using a utility function, much in the way we have done above. This is an interesting line for further work.

Many other potentially interesting models suggest themselves, but so far apparently have not been investigated. Possible topics to cover are:

- o Economies with both a renewable resource (agriculture) and a non-renewable resource (say copper mining).
- o Economies with a renewable resource and capital accumulation. Most optimal control models with renewable resources ignore capital (Clark 1976, Smith 1977). Clark et al (1979) give a partial equilibrium model here which could perhaps be turned into a general equilibrium model of interest.
- o Economies with two renewable resources (forestry and agriculture) where excessive use of one resource imposes external costs on the other (e.g. floods, siltation).
- o Modelling the effect of open access versus private ownership of renewable resources is also necessary (similar to the modelling of non-cooperation versus social optimality in the models of Section 7.1 and 8.1).

The intergenerational equity literature has looked at some of these areas. For example, Okuguchi (1979) formulates a model using capital, labour and several renewable and non-renewable resources as inputs to production. By assuming that all inputs are substitutable at the margin, he not surprisingly shows that maintaining the stock of just renewable resources is not necessary for sustainability. However, there is no analysis of optimal (as opposed to sustainable) paths for the economy, or of open access effects.

10. INCOME DISTRIBUTION AND SUSTAINABLE DEVELOPMENT.

The applications in Sections 5-9 have all ignored the distribution of income or welfare within the society being considered; all that mattered was aggregate consumption and aggregate environmental quality, etc. Yet as Section 3.9 pointed out, the ethical concern for intergenerational equity underlying sustainability notions is naturally associated with an ethical concern for intragenerational equity. We give this some thought here, although this is one of the less satisfactory sections of this draft no consistent models have yet been worked out.

An immediate question is: what is the policy connection between intergenerational and intragenerational equity? Do policies to redistribute income within a society (if that is what society wants) necessarily have any connection with sustainability policies? On a small scale - say at the level of a small developing country - two connections are possible.

One connection derives from the frequent observation (crudely modelled in Section 9, and reflected in WCED quote 3 and World Bank quote 5 in Appendix 1) that very poor people may be driven to destroy their environment; desertification of grazing areas in the Sahel is perhaps the best known example. So any policy to help these poor people must take environmental dependencies into account. Moreover, environmental degradation frequently affects other parts of society, as deserts encroach upon cropland, or as deforestation high in a watershed drives genetically valuable species to extinction, and causes floods and sedimentation problems downstream. But by definition, people who are so poor that they are driven to destroy their environment will not be able to pay anything for the external damage they are causing elsewhere. The Coase theorem, that the allocation of property rights will not affect the allocation of environmental resources (see Section 7.3) does not hold here. If property rights are effectively given to the poor, their wealth will be greatly increased and the environment will be affected. The rest of society (presumably richer) will have an interest in paying the poor not to destroy their environment, which will simultaneously improve the environment and redistribute income.

The second connection, noted by the World Bank (1987, p6) is that poor people are often the greatest victims of pollution. The property rights perspective is again interesting here. If the wealthy industrialist effectively owns the rights to the environment, pollution will continue at a high level because the poor who suffer the pollution can pay very little (say X) to have the pollution reduced. However, if environmental property rights are transferred to the poor - clearly an act that redistributes wealth, since such rights are valuable - then the industrialist will have to pay the poor enough to make them willing to accept a given level of pollution. This payment may be much higher than X, and the industrialist will find it worthwhile to reduce pollution significantly. So in both cases, policies that effectively give environmental property rights to the poor should both improve the environment and alleviate poverty. Whether they will also contribute to sustainable economic growth is another matter, not yet considered here.

At a global level the redistribution question is inextricably connected to the environment, because the question is (Ayres 1988b): how do we permit the LDC's to industrialize without destroying the environment? In other words, how do we tackle the problem of intragenerational equity without making it impossible for future generations to enjoy our standard of living? If we believe that it is ecologically impossible for the whole of the human race to enjoy anything like the current standard of living of Western industrialised nations - and this raises empirical questions about the limits of capital-resource substitution raised in Section 8.2 above - then "equitable" sustainable development will require a reduction in the living standards of rich nations, as WCED (1987, quote 4) implies.

One interesting, if politically fanciful mechanism for such a international transfer of wealth might be a compensation fund for cumulative global pollution problems, such as the greenhouse effect and ozone depletion. Payments into the fund would be made in proportion to nations' cumulative contributions to the problem (so that rich nations pay most) and payments out

from the fund would be made in proportion to damages cause by the problem (so that all nations receive a fair share.)

11. ARE DISCOUNT RATES TOO HIGH?

11.1 Discount rates and sustainability

The question addressed here is the perennial one of whether the discount rates used for cost-benefit analyses of both public and private investment projects, are in some sense "too high" when the projects involve long term environmental costs or benefits. We are talking here about the discount rate for goods and services, and we will henceforth call it the interest rate, to avoid confusion with the utility discount rate δ used so far in this paper; the relationship between the two is shown in Section 11.3. The arithmetic is well known: a 10% real interest rate reduces a \$100 sum 50 years hence to a present value of less than \$1 now, etc. This sort of discounting may lead us to choose projects which do long term environmental damage and harm prospects for future sustainability. Our approach here reviews standard analyses (both positive and normative) of discount rate issues, and adds in the second half of Section 11.2 a novel, purely environmental reason why interest rates may be too high. Much of the discussion springs from ideas in Markandya and Pearce's recent papers (1988a, 1988b), which will here be referred to as MPa and MPb, and from Page (1983), who commented (p57):

"How 'the discount rate', and hence all interest rates are to be manipulated is usually left unclear. Presumably, adjustments are to be done through the tax structure, or perhaps through monetary policy."

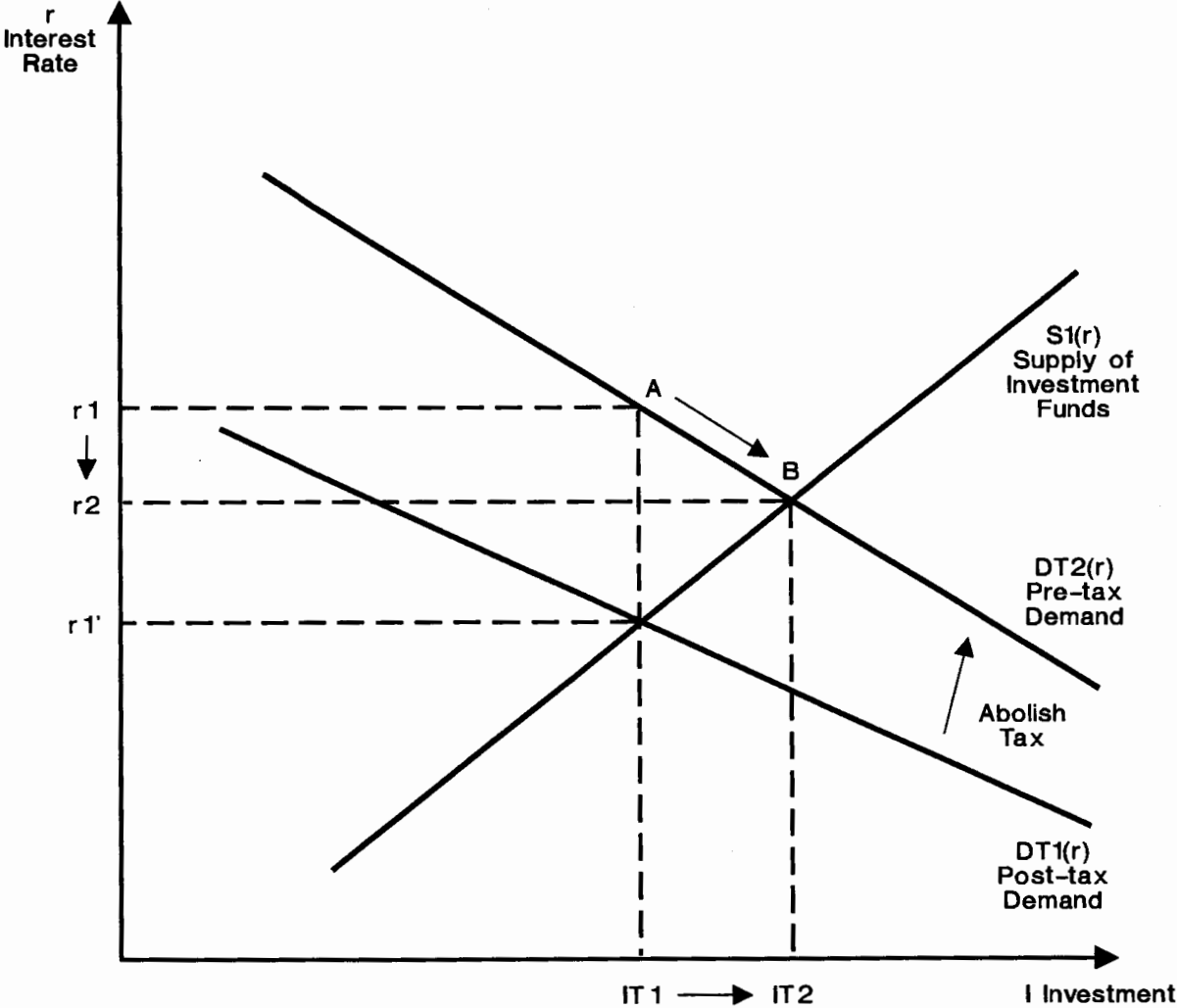
We focus here on manipulation of the tax structure and ignore monetary policy.

11.2 Changing the demand for investment funds

The interest rate is the market price of investment funds, and its level is therefore determined, like any other price, by the interaction of supply and demand. Let us first concentrate on the demand for investment funds, and let us suppose (as is the case in most developed countries) that investment income is taxed. This drives a wedge between the rates of return earned by borrowers and savers, illustrated in Figure 14. The supply of funds is $S_1(r)$, the pretax demand for funds (the gross return to investors) is $DT_2(r)$, and the posttax demand (the net return that investors can pay to savers) is $DT_1(r)$, where r is the interest rate (all measured in real terms). Equilibrium is at A, with total investment equal to IT_1 , an opportunity cost of capital r_1 (we are most interested in this because this is the main interest rate used to discount costs and benefits in project appraisal, especially in the private sector) and a consumption rate of interest r_1' .

Whether or not r_1 , r_1' , or some combination of the two should be used for various types of public sector project appraisal has long been a subject of debate, and revolves around how much public investment displaces private investment, and how much returns are reinvested and how much are consumed (Marglin 1963b). MPb suggest using some mean of the two, but Kolb and

Figure 14: REMOVING INVESTMENT INCOME TAX LOWERS THE INTEREST RATE



Scheraga (1988) suggest an innovative two-stage approach whereby capital costs are first annualised at r_1 , then all annual costs and benefits are discounted at r_1' . This is not our concern here, and suppose now that investment income tax is abolished. (This reduces a market distortion and so would generally be regarded as welfare-enhancing, although it has effects on income distribution and government revenues.) The net demand for funds now rises to DT_2 , and the new equilibrium is at B, with higher total investment IT_2 and a lower opportunity cost of capital (interest rate) r_2 .

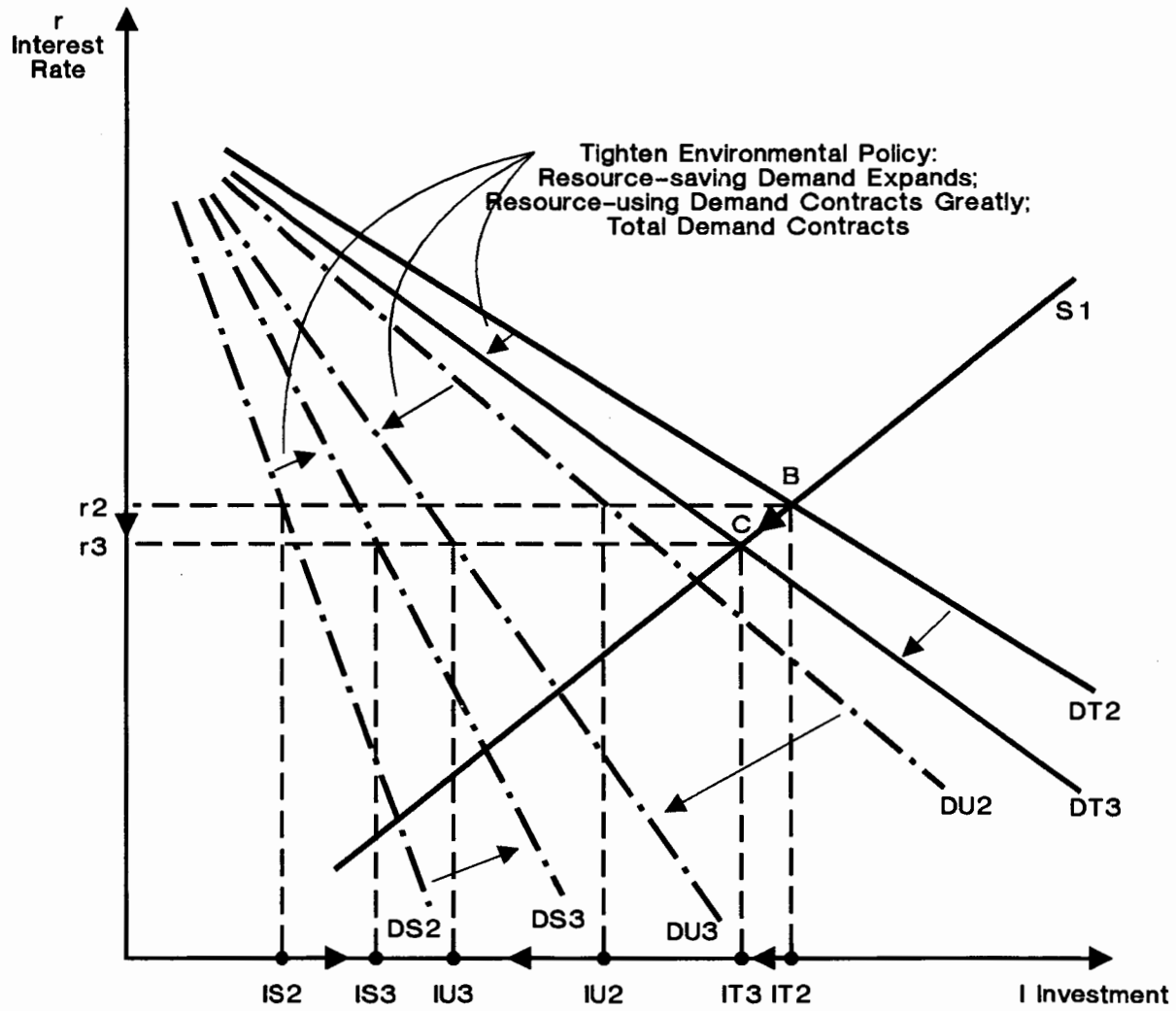
Next, suppose that the new total demand for funds DT_2 can be divided in the manner suggested in Section 8.2, that is into the demand DU_2 derived from investments that are **resource-using** (i.e. cases where capital and natural resources are complements) and the demand DS_2 derived from investments that are **resource-saving** (cases where capital substitutes for resources). Total investment is IT_2 , divided into resource-using investment IU_2 and resource-saving investment IS_2 , as shown in Figure 15.

In drawing these curves we assume that resource-using investment is dominant. There is little evidence either way on this crucial empirical assumption, but some other authors seem to agree with it. Page (1983, p54) comments: "As an empirical matter, it appears that with the present accumulation of man-made capital, dependence on the physical resource base is growing, not shrinking." MPb (p30) simply state that "Since natural resources are required for investment..". This implies that all investment is resource-using in net terms, which seems to go too far, but it supports our assumption.

Suppose also that environmental policy is currently far from complete, so that the material resource flow connected with every investment causes many external costs and benefits. For resource-using investments the external costs are assumed to significantly outweigh the benefits, and the converse is assumed for resource-saving investments (more crucial empirical assumptions). Now let a tougher environmental policy be introduced, which internalises many more externalities. The accounting cost of resources used or saved in both types of investment projects will then be driven up. On Figure 15 this will shift the resource-using investment demand curve inward to DU_3 , the resource-saving demand curve outward to DS_3 , and (because of our assumption that resource-using investment is dominant) on balance the total demand curve shifts inward to DT_3 . Given an unchanged supply curve S_1 , market equilibrium moves from B to C, investments move to IU_3 (decrease), IS_3 (increase) and IT_3 (a net decrease), and the market-clearing interest rate drops to r_3 .

As shown in Section 7, a tougher environmental policy is likely to make development more sustainable (the shift from resource-using to resource-saving investment will itself sustainability), and this is consistent with the lower market interest rate that it causes, since lower interest rates give relatively more weight to the distant future in present value calculations. Another policy observation is that if environmental policy takes the form of revenue-generating market mechanisms such as emission charges or auctioned marketable emission permits, the revenue raised could balance out the above loss of revenue from abolishing investment income tax. A similar idea has been explored empirically for the U.S. by Terkla (1984).

Figure 15: TIGHTENING ENVIRONMENTAL POLICY MAY LOWER THE INTEREST RATE



DS = Demand for funds for "resource-saving" investments
 DU = Demand for funds for "resource-using" investments
 DT = Total demand for investment funds

11.3 Changing the supply of investment funds

Let us finally look at the supply of investment funds. The interest rate r that a lender requires to divert his income from consumption to investment (the "consumption rate of interest") can be divided into two parts as follows:

$$r = \delta - \dot{u}_c / u_c \quad (\text{MPa, p3, with different notation})$$

where δ = the utility discount rate used in the optimal growth models above, and u_c is the (expected) marginal utility of per capita consumption. Assuming for simplicity that $u = (c - c_m)^\nu$, $0 < \nu < 1$, c_m = subsistence consumption, then

$$r = \delta + (1 - \nu)\dot{c} / (c - c_m) \quad (*)$$

When aggregated over several different consumers this gives the supply curve $S_1(r)$. If savers care about future generations in general as well as their own heirs, this process of aggregation leads a supply of investment funds which may be less than is socially optimal at any given interest rate. This is the well-known "isolation paradox" (Marglin 1963, Sen 1967). We can thus see three ways in which the supply curve can be shifted to the right, leading to a still lower equilibrium interest rate:

- (1) The utility discount rate δ is lowered. Lowering the utility discount rate is likely to reduce resource depletion rates and increase sustainability, as we saw in Sections 6 and 7, but the case for such lowering is a purely moral or ethical one (Parfit 1983).
- (2) The expected growth of consumption $\dot{c} / (c - c_m)$ in the future is lower. Suppose a lender expects the past growth rate of his consumption to continue into the future, but there is some reason, unbeknown to the lender, why it will not - perhaps the thermodynamic limitations mentioned in Section 8.2. Then if the lender is informed of this reason, his expected $\dot{c} / (c - c_m)$ will drop and his supply curve will shift to the right.
- (3) Saving is subsidised in some way, to correct for the isolation paradox.

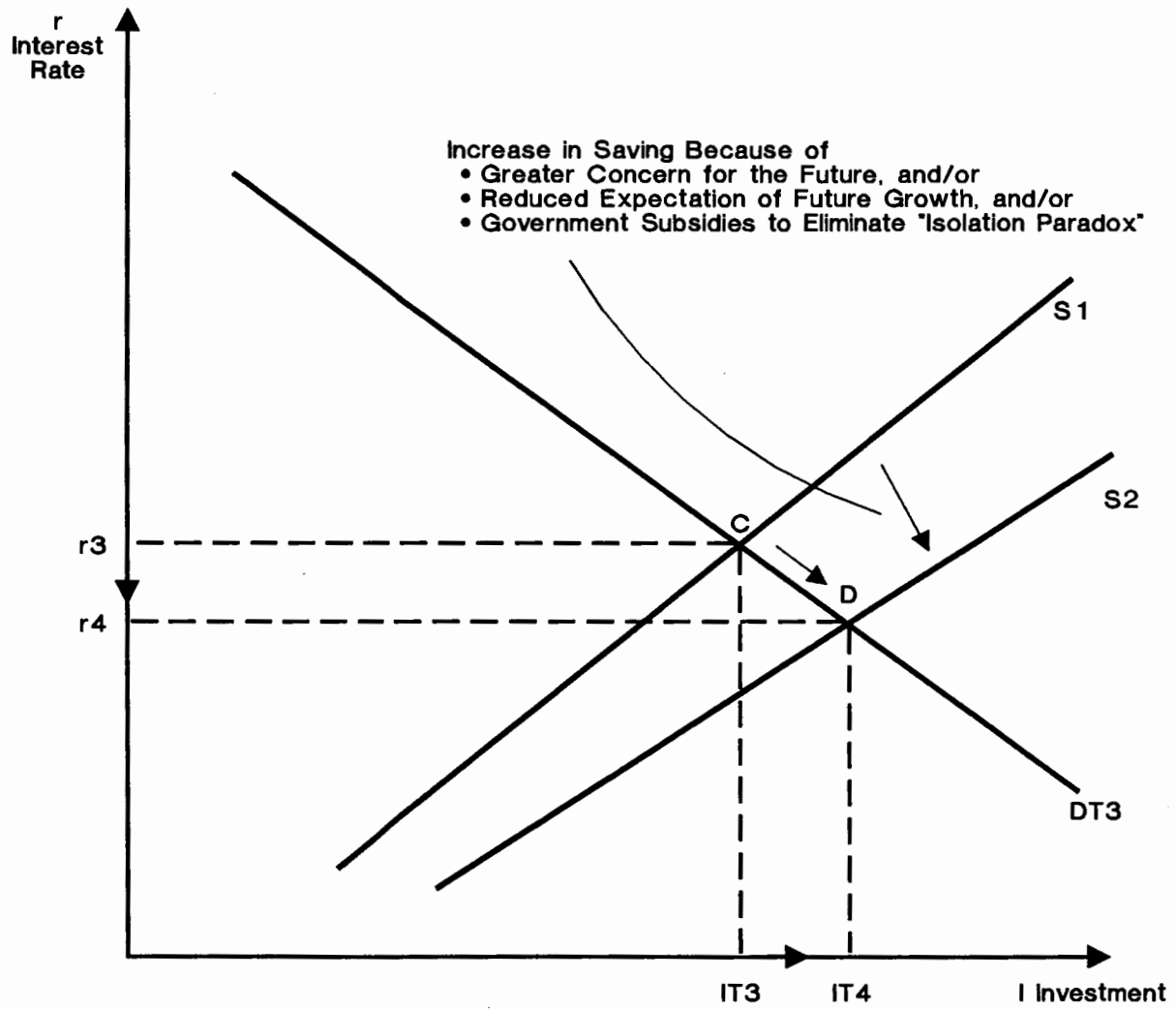
Figure 16 gives a diagrammatic analysis of these changes. Any or all three of them will increase the supply of investment funds from S_1 to S_2 , moving the equilibrium point from C to D , increasing total investment from IT_3 to IT_4 , and lowering the interest rate yet again from r_3 to r_4 .

11.4 Interest rates in developing countries

A good test of the above analysis, will be if it can help explain the common observation that real interest rates are much higher in developing countries than in developed countries. We can suggest some reasons, although these are only very tentative.

On the supply side, one reason for high discount rates is poverty. Someone close to subsistence is likely to have a very high consumption discount rate, as shown in equation (*) above if c is only just above c_m . This is not the

Figure 16: INCREASED SAVING LOWERS THE INTEREST RATE



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same as saying he has a high utility discount rate: he may care a lot about his future welfare per se, but any change in his consumption level will have such a big effect on his welfare that his consumption discount rate is very high. Another, related effect on supply may be that the probability of dying in the near future depends on consumption (Zarembka 1972, pp73-81).

On the demand side, the observation in Section 5 that environmental property rights tend to be very weak in "frontier" developing countries is relevant here. Suppose for example that traditional communal management of tropical forests has been disrupted, but modern private ownership has not yet been established. Then both the marginal user costs (depleting the forest reserve left for future generations) and the marginal external costs (soil erosion and climate change) of deforestation will be ignored (Pearce and Markandya 1987). The situation may be made even worse by explicit subsidies to deforestation (Repetto 1988a). Therefore the logging company perceives a rate of return well above the social rate of return and hence logs at a greatly excessive rate.

Therefore if natural resource exploitation is especially dominant and property rights very weak in a country's economy, policy changes to establish proper ownership of resources, and to eliminate unwarranted subsidies for their exploitation, will not only alter the perceived costs and benefits of exploitation at any point in time. They may also lower the interest rate in the whole economy. This then encourages investors to take a longer term view and treat forests, etc, as sustainable rather than depletable resources.

12. INFORMATION AND UNCERTAINTY

So far we have assumed perfect information in all our sustainability models. In reality information is never perfect, and ignorance abounds. Maybe many poor farmers, burning down a patch of rainforest in Amazonia to make a smallholding, don't know that the soil becomes depleted and worthless after a few years. Maybe governments don't realise how faulty their resource policies are. Much unsustainable exploitation of natural resources could be explained by ignorance, and much of the current research effort on sustainable development is directed at overcoming such ignorance.

A rather different form of imperfect information is the inherent uncertainty of the future. Previous sections contain only one recognition of this, in Section 11.3 where it is pointed out that expectations about future rates of consumption growth may be ill-informed. Yet risk and uncertainty (we make no distinction here) are pervasive on the timescales to which sustainable development concepts apply, and cannot be ignored. Unfortunately it is beyond the scope of this paper to present a full analysis of risk - further work is clearly needed here - and we can only refer to some key results. Intuitively, it is easy to see that the increased variability of possible future environmental damage (about an unchanged mean) justifies a more cautious environmental policy, even for a risk-neutral policy-maker. Risk aversion merely strengthens the conclusion. Yet further caution is justified if there are thresholds, beyond which environmental damage may be catastrophic and irreversible, meaning that the worst that can happen to the environment is

much further below the mean than the best that can happen. These are broadly the conclusions reached by Siebert (1987, Chapter 14) using a formal model of optimal (not sustainable) decision-making under environmental risk from cumulative but assimilable pollution. He finds that:

- o "...an increased uncertainty in the damage function implies a lower level of pollution."
- o "...if risk aversion is increased, the steady state [requires] a higher penalty on emissions."
- o "...an increased uncertainty in the assimilative capacity of the environment implies a lower level of pollution."
- o "With the environmental impact of pollution being uncertain, a higher environmental quality is optimal in the steady state. ... Higher environmental quality can be interpreted as an insurance against the risk of environmental degradation or as a risk premium."
- o "A solution of handling irreversibilities is to explicitly introduce an option value being defined as the value...that arises from retaining an option to a good or service for which the demand is uncertain."

13. OPERATIONALITY: PUTTING THE IDEAS INTO PRACTICE

Assuming that a sustainability criterion is accepted as socially desirable, how can it be put into practice? In exploring this question, this section pulls together some of the diverse threads of this paper. The dangers of simply talking about "sustainability" are obvious from the numerous different definitions given in Section 3, but they all have in common the notion of concern that the aggregate welfare of future generations should be protected in some way. We will try to be more specific where this is necessary, although as in other places in this paper the issue of intragenerational equity is largely ignored.

There seem to be three separate questions concerning operationality:

- (1) To what system should the sustainability criterion apply?
- (2) Is a separate sustainability criterion is necessary in practice?
- (3) Can a sustainability criterion be made operational?

These are now discussed in turn, the first briefly and the latter two in more depth.

13.1 To what system should the sustainability criterion apply?

This is essentially the question raised in Section 3.5: does every resource need to be conserved, or are tradeoffs acceptable? Can resource accounting help us to make aggregate judgments about such tradeoffs? A similar, although

more radical question is: does every country have to experience sustainable development? Or can some rise and some fall? In any case it is clear that we need to define the system to which a sustainability policy is to apply, before we can answer questions (2) and (3). Policies for sustaining a narrowly defined ecosystem, or even a single species, will look very different from policies for global sustainability. Exogenous factors, such as resource prices and environmental effects from outside the system, will be very different at different levels of system. Only at the global level will all such factors be endogenously determined within the system.

13.2 Is a separate sustainability criterion necessary in practice?

The case against a separate sustainability policy is that sustainability, while clearly desirable as a social goal, will be achieved in the course of pursuing the more operational goals of a proper environmental policy. This view was discussed in Section 7.2. The models of Sections 7 and 8 suggested how the inescapable physical connection between resource depletion and environmental externalities, meant that conventional environmental policies to internalise these externalities (policies that are stressed throughout the World Bank 1987 paper) are inherently likely to reduce resource depletion and promote sustainability. Recall from Section 7.3 that internalising externalities does not necessarily mean governments intervening with regulatory controls or economic incentives to "make polluters pay". In some instances the definition and enforcement of property rights over the environment will be enough; although who gets these property rights may have a big impact on both income distribution and environmental quality, if polluters and pollutees have very different income levels, as noted in Section 10.

It is of course very hard to know in practice whether a full environmental policy will automatically achieve sustainability (Case A2 in Figure 10) or not (Case B). The practical view here is that since:

- (a) there are so many problems to overcome in developing a coherent and rigorously enforced environmental policy, particularly in developing countries where subsidies which actually encourage depletion and pollution are common;
- (b) environmental policy will probably help sustainability automatically;
- (c) it is very hard to measure aggregate sustainability anyway;
- (d) it is even harder to apply sustainability criteria to individual projects (see Section 13.3);
- (e) ethical principles of intergenerational equity, which have to be invoked to justify sustainability, are not necessary to justify environmental policy;

- policy efforts should therefore be confined to promoting conventional environmental policies, perhaps using a sustainability rhetoric if this proves politically useful, but leaving sustainability policy per se to academic discussions (such as this?).

The opposite point of view is that sustainability is a real problem, particularly at the global level (see for example Daly 1986, 1987). There is indeed no guarantee that the fully optimal state achieved by thorough environmental policies will be sustainable: the world (or what ever system we

are concerned with) may be like Case B in Figure 10. The discussion on ultimate physical limits to growth in Section 8.2 is relevant here. Particular importance is attached to rising global levels of cumulative pollution: the greenhouse effect and ozone depletion will probably affect most countries, and may cause serious harm both to amenity and to productivity (the distinction between the two was defined in Section 2 and explored in Sections 7 and 8). We cannot resolve this complex empirical debate here, so we turn to the main question that is relevant when sustainability is a problem: how could a sustainability criterion be applied in practice?

13.3 Can a sustainability criterion be made operational?

This question has to be addressed at two levels, the system level and the project level; hence the importance of first defining what system we are concerned with (Section 13.1). In general, if the system is small and homogeneous, it may be possible to measure sustainability (assuming that influences from outside the system do not change) and to devise sustainability policies; but it will be harder to justify both making sustainability of this particular subsystem into an important objective, and ignoring possible changes in outside influences.

As already noted, the difficulties of measuring sustainability of a large, heterogeneous system are obviously great. Liverman et al (1988) find serious weaknesses in all readily available measures of sustainability, and these can only be put right with great efforts of resource accounting and simulation modelling. But let us assume that somehow they are overcome, and it has been determined that the system is unsustainable, or nearly unsustainable, even with all environmental externalities internalised. What policies follow?

At the system level, we will find that the depletion of some resources, or some resource aggregate, needs to be controlled. This may be an absolute limit to depletion, if there is a minimum stock of a critical resource (say the land area of a game reserve, if we want to sustain a particular species) below which the system is unsustainable, or just a slowing down of depletion to allow natural growth, capital accumulation or technical change enough time to replenish the "effective resource base". Either way, there must be some aggregate constraint, imposed from outside, on the total rate of resource depletion in the system (Daly 1986). This constraint could be regulatory (legal bans or limits on particular resource uses), or economic (conservation incentives to slow down depletion, as modelled in Sections 7 and 8), or a combination of both. What will happen in either case is that the effective price of the resource will be driven up (perhaps to infinity) throughout the system, inducing conservation in countless separate project decisions.

Obvious illustrations of this philosophy are constraints on global emissions of CFCs or CO₂. These constraints must be set at a global (or near-global) level, whether through regulation (such as the Montreal Protocol for CFCs) or market mechanisms (a mooted global carbon tax). Prices of CFCs or fossil fuels to final users will rise, and conservation efforts will be induced. Together with other system-level sustainability policies, this may cause sufficient changes in resource prices for the market rate of interest to be lowered so that all project appraisals automatically give greater weight to

future generations (see Section 11). The political and scientific problems of making a sustainability criterion operational at a system level are daunting, but at least the concept is fairly obvious.

Another approach is that of **intergenerational compensation**. This idea is at the heart of Hartwick's rule (Hartwick 1977): the current generation should compensate the future for depleting non-renewable resource stocks by investing in enough capital that the productivity of the resources-capital aggregate is preserved. The idea is extended by Spash and d'Arge (1988) to include compensation in the form of increased technical knowhow or specific bequests of goods. Policies to achieve such compensation might not look very different from the sort of constraints that were suggested above for CFC and CO2 use.

But how could a sustainability criterion work at a project level, where a project is only a small part of the overall system that is to be sustained? How indeed: there is a profound conceptual problem here, deriving from the mathematical definition of sustainability as a constraint rather than a maximisation rule like optimality. The integral in Table 2 that the optimality criterion seeks to maximise is a sum of discounted utility costs and benefits for the whole system. It is thus possible to work out whether or not an individual project helps or hinders optimality, by summing its own discounted monetary costs and benefits. Several big assumptions have to be made in this process (crucially that the marginal utility of income is constant and that the distribution of costs and benefits is irrelevant) but at least the final procedure (cost-benefit analysis) is conceptually obvious, and more or less operational at the project level.

But how can we say whether or not an individual project contributes to system sustainability? If sustainability means that aggregate welfare shall not decline, is any project that decreases welfare at any future time considered harmful to sustainability, even if it greatly increases welfare at other future times? This would be an absurd conclusion, and so the notion arises that project costs and benefits must somehow be smoothed out over time before we can judge its contribution to system sustainability. This in turn leads to the notion of **intergenerational compensation projects**, a concept that clearly attracts a lot of support: see for example Pearce (1983, p75), Tietenberg (1984), World Bank (1987, p8), Markandaya and Pearce (1988a, pp10-11), Pearce, Barbier and Markandya (1988, Section 11), and d'Arge (forthcoming, p328). The following quotes illustrate the approach:

"If a particular project being considered maximises the present value, but confers some unacceptably low or negative net benefits on future generations, then some of the current gains could be set aside as a trust fund to compensate for the negative net benefits.....Whatever its form, the compensation mechanism provides a way of sharing maximum net benefits among generations without resorting to a policy that wastes net benefits in a misguided search for intergenerational fairness." (Tietenberg p432)

"Sustainability can be introduced into cost benefit analysis by setting a constraint on the depletion and degradation of the stock of natural capital. Essentially, the economic efficiency objective is modified to mean that all projects yielding net benefits should be undertaken subject

to the requirement that environmental damage (i.e. natural capital depreciation) should be zero or negative. However, applied at the level of each project such a requirement would be stultifying. Few projects would be feasible. At the programme level, however, the interpretation is more interesting. It amounts to saying that, netted out across a set of projects (programme), the sum of individual damages should be zero or negative." (Pearce, Barbier and Markandya, Section 11, authors' emphasis)

This seems a fine concept that can be made operational. It is already being applied, with for example a recent proposal to replant forests in Central America as compensation for the carbon dioxide that will be produced by a new power station in New England. However, many questions are still unanswered. Logically, compensation projects seem to be neither sufficient nor necessary to achieve system sustainability. How are we to judge what is an unacceptably low net benefit for future generations, and for which generations? What if investments in the trust fund themselves affect sustainability? How is a "programme" of projects to be defined? If there are many programmes, should not the criterion of zero or negative aggregate environmental damage be applied to the collection of all programmes?

Above all, how can the compensation idea work in the private sector? How can one define a programme if there are countless small private investors instead of one big agency? Even if one can, who will carry out the uneconomic "compensating project" designed to balance out the environmental damage of the other, economic projects.

It may be concluded from considering overall system sustainability - particularly in the case of poor countries where sustainability can be reduced to sustainable resource use (see Section 3.5) - that the stock of some particular resource must be absolutely protected, or other resource targets and rules of thumb set. One may then lay down rules that a project depleting the resource must be compensated by an "environmental improvement" project regenerating that resource (Markandya and Pearce 1988, pp10-11). But how can this be applied to non-renewable resources, or several resources which are substitutable for each other?

Returning to the example of global pollutants illustrates some of these points. If global carbon dioxide emissions are posing a threat to sustainability, it is hard to see how specific compensation mechanisms for individual projects can help. For countless, private, daily decisions on fossil fuel burning - how high to set the room heating thermostat, whether or not to drive to work, how many trees to cut down and burn today - affect carbon dioxide emissions and long term climate change. What would be suitable compensating investments anyway? The more appropriate policy seems to be to set a system-level constraint on carbon use. Then the resultant higher prices for carboniferous fuels will work their way through normal market mechanisms and encourage the appropriate intergenerational compensation (more investments in energy conservation) in these millions of daily decisions.

14. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

A few broad conclusions of the paper seem worth restating here. Firstly, almost all approaches to sustainable growth or sustainable development contain the same core ethic of intergenerational equity, that future generations are entitled to at least as good a quality of life as we have now. Quality of life is a broad concept entailing much more than per capita consumption of marketed goods and services. A neoclassical formalisation of the core ethic is that utility (equivalent to quality of life) should not decline, although this may allow tradeoffs between various aspects of life that some consider should be non-tradeable. One important part of sustainability not covered by the core ethic is that of intragenerational equity.

Secondly, the way in which the core ethic is translated into a set of conditions for sustainability is highly dependent on the context. Sustainability conditions for a small developing country over the next decade, for the U.S.A. over the next century, and for the entire planet over the next millenium, will all look very different. Deriving sustainability conditions inevitably requires judgments on which natural and anthropogenic resources are essential to production and to welfare, and on the extent to which these resources are substitutable for each other. Many conditions can be seen as "maintaining the capital stock intact", but this does not avoid the need for these judgments. The existence of natural thresholds, beyond which environmental damage is irreversible and possibly catastrophic, may represent a significant limit to the substitutability of capital and technological knowledge for natural resources.

Thirdly, although sustainability has ethical foundations that lie outside the mainstream of neoclassical welfare economics, neoclassical analysis can be illuminating and should not be rejected. In particular, it can show how conventionally justified environmental policies may make the economy more sustainable as an automatic side-effect.

Suggestions for further work include:

- o More analysis of general equilibrium growth models using renewable (as opposed to non-renewable) resources. Various models need to allow for capital accumulation, technological development and possibly a mix of renewable and non-renewable resources, as suggested in Section 9.
- o The idea that stricter environmental policy can lower the economy-wide interest rate (Section 11) warrants further theoretical and empirical scrutiny. Included in this needs to be more analysis of why real interest rates are so high in developing countries.
- o The roles of both common property and open access regimes of renewable resource management need to be related to sustainability. This is particularly to explain why some natural resource systems that have long been stable in some developing countries suddenly become unsustainable, and perhaps then to suggest how open-access global resources like the stratosphere and oceans can be sustainably managed as global commons.

- o The public choice approach to government decision-making needs much greater attention. It has to be explained why so many governments encourage unsustainable resource practices, and how they are going to be persuaded to change their policies.

- o Last and perhaps most importantly, the importance of uncertainty about the future, in making potentially irreversible decisions about the management of natural resources, needs much greater exploration than has been provided in Section 12. Threshold effects and uncertainty might combine to give a conventional economic justification of preserving physical stocks of natural capital in order to guarantee sustainability, a justification that is not provided by the perfect information, marginalist analysis of this paper.

Boulder, 1 January 1989

APPENDIX 1 DEFINITIONS OF SUSTAINABILITY IN THE LITERATURE

This Appendix is not exhaustive, but it gives a good idea of the variety of definitions of sustainability concepts that have appeared in the last decade, and of the people who use such concepts. (Bold type is added where appropriate to emphasise which concepts are being defined.)

Allen (1980) - summarising IUCN (1980)

1. "Sustainable utilization is a simple idea: we should utilize species and ecosystems at levels and in ways that allow them to go on renewing themselves for all practical purposes indefinitely." (p18)
2. "The importance of ensuring that utilization of an ecosystem or species is sustainable varies with a society's dependence on the resource in question. For a subsistence society, sustainable utilization of most, if not all its living resources is essential. ... The greater the diversity and flexibility of the economy, the less the need to utilize certain resources sustainably, but by the same token the less the excuse not to." (p18)
3. "...it is essential...to ensure that...people protect those parts of the biosphere that need protecting and modify the rest only in ways that it can sustain." (p20)
4. "**sustainable development** - development that is likely to achieve lasting satisfaction of human needs and improvement of the quality of human life" (p23)

Barbier (1987) - academic economist

1. "...the concept of **sustainable economic development** as applied to the Third World...is therefore directly concerned with increasing the material standard of living of the poor at the 'grassroots' level, which can be quantitatively measured in terms of increased food, real income, educational services, health-care, sanitation and water supply, emergency stocks of food and cash, etc., and only indirectly concerned with economic growth at the aggregate, commonly national, level. In general terms, the primary objective is reducing the absolute poverty of the world's poor through providing lasting and secure livelihoods that minimize resource depletion, environmental degradation, cultural disruption and social instability." (p103)

Brown et al (1987) - environmental scientists

1. "In the narrowest sense, **global sustainability** means the indefinite survival of the human species across all the regions of the world. A broader sense of the meaning specifies that virtually all humans, once born, live to adulthood and that their lives have quality beyond mere biological survival. Finally the broadest sense of global sustainability includes the persistence of all components of the biosphere, even those with no apparent benefit to humanity." (p717)

Burness and Cummings (1986) - academic economists

1. "Professor Daly's notion of "sustainability" [in Daly 1986] is extraordinarily vague and ill-defined. ...in a pedagogical sense sustainability requires that all processes operate only at their steady state, renewable level, which might then suggest a return to a regulated caveman culture." (p323)

Clark (1986) - environmental scientist and policy analyst, IIASA

1. "A major challenge of the coming decades is to learn how long-term, large-scale interactions between environment and development can be better managed to increase the prospects for ecologically sustainable improvements in human well-being." (p5)

Coomer (1979)

1. "[The] sustainable society is one that lives within the self-perpetuating limits of its environment. That society...is not a 'no-growth' society. ... It is, rather a society that recognizes the limits of growth...[and] looks for alternative ways of growing." (p1)

Daly - academic economist

1. "The market does not distinguish an ecologically sustainable scale of matter-energy throughput from an unsustainable scale, just as it does not distinguish between ethically just and unjust distributions of income. Sustainability, like justice, is a value not achievable by purely individualistic market processes." (1986, p320).

2. "By 'growth' I mean quantitative increase in the scale of the physical dimensions of the economy; ... By 'development' I mean the qualitative improvement in the structure, design and composition of physical stocks and flows, that result from greater knowledge, both of technique and of purpose." (1987, p323)

Georgescu-Roegen (1988) - academic economist

1. "...'growth' is if you get just an increasing number of the same type of mail coaches. And if you pass from traveling in mail coaches to traveling by railway, that is 'development'." (pS294)

Goodland and Ledec (1987) - institutional environmental scientists

1. "Sustainable development is here defined as a pattern of social and structural economic transformations (i.e. 'development') which optimizes the economic and societal benefits available in the present, without jeopardizing the likely potential for similar benefits in the future. A primary goal of sustainable development is to achieve a reasonable (however defined) and equitably distributed level of economic well-being that can be perpetuated continually for many human generations." (p36)

2. "...sustainable development implies using renewable natural resources in a manner which does not eliminate or degrade them, or otherwise diminish their usefulness for future generations.....Sustainable development further implies using non-renewable (exhaustible) mineral resources in a manner which does not unnecessarily preclude easy access to them by future generations..... Sustainable development also implies depleting non-renewable energy resources at a slow enough rate so as to ensure the high probability of an orderly societal transition to renewable energy sources....." (p37)

Howe (1979) - academic economist

1. "GUIDELINES FOR A RESPONSIBLE NATURAL RESOURCES POLICY

(6) ...activities should be considered that would be aimed at maintaining over time a constant effective natural resource base. This concept was proposed by Page (1977) and implies not an unchanging resource base but a set of resource reserves, technologies, and policy controls that maintain or expand the production possibilities of future generations." (p337)

Markandya and Pearce (1988) - academic economists

1. "The basic idea [of sustainable development] is simple in the context of natural resources (excluding exhaustibles) and environments: the use made of these inputs to the development process should be sustainable through time.If we now apply the idea to resources, sustainability ought to mean that a given stock of resources - trees, soil quality, water and so on - should not decline." (pp9-10).

2. "...sustainability might be redefined in terms of a requirement that the use of resources today should not reduce real incomes in the future...". (p11)

Morey (1985) - academic economist

1. "...much of the desertification literature also suggests that desertification is nonoptimal from both the producer's and society's perspective. Sustainable use is generally put forward as the optimal strategy." [Morey then shows how sustainable land use may or may not be optimal] (p551)

O'Riordan (1988) - academic environmental scientist

1. "It may only be a matter of time before the metaphor of sustainability becomes so abused as to be meaningless, certainly as a device to straddle the ideological conflicts that pervade contemporary environmentalism." (p29)

2. "Sustainability is a much broader phenomenon [than sustainable development], embracing ethical norms pertaining to the survival of living matter, to the rights of future generations and to institutions responsible for ensuring that such rights are fully taken into account in policies and actions." (p30)

Pearce - academic economist

1. "The sustainability criterion requires that the conditions necessary for equal access to the resource base be met for each generation." (1987, p13).
2. "In simple terms [sustainable development] argues for (a) development subject to a set of constraints which set resource harvest rates at levels no higher than managed or natural regeneration rates; and (b) use of the environment as a 'waste sink' on the basis that waste disposal rates should not exceed rates of (natural or managed) assimilation by the counterpart ecosystems. ... There are self-evident problems in advocating sustainable rates for exhaustible resources, so that 'sustainability' tend to think in terms of a resource set encompassing substitution between renewables and exhaustibles. Equally self-evident is the implicit assumption that sustainability is a 'good thing' - that is optimising within sustainable use rates is a desirable objective. On these terms, sustainability could imply use of environmental services over very long time periods and, in theory, indefinitely." (1988a, p58)
3. "The key concept [regarding natural resource degradation in developing countries] is 'sustainability'. Changes in resource management practice toward sustainable resource use could at least contribute to the preservation of the renewable resource base, and hence to the direct well-being of the population and to the future of the macroeconomy." (1988b, p102)

Pearce, Barbier and Markandya (1988) - academic economists

1. "We take development to be a vector of desirable social objectives, and elements might include:
 - increases in real income per capita
 - improvements in health and nutritional status
 - educational achievement
 - access to resources
 - a 'fairer' distribution of income
 - increases in basic freedoms....Sustainable development is then a situation in which the development vector increases monotonically over time." (p4)
2. "We summarise the necessary conditions [for sustainable development] as 'constancy of the natural capital stock'. More strictly, the requirement as for non-negative changes in the stock of natural resources such as soil and soil quality, ground and surface water and their quality, land biomass, water biomass, and the waste assimilation capacity of receiving environments." (p6)

Pirages (1977) - from conference funded by the Institute for World Order

1. [Sustainable growth] means economic growth that can be supported by physical and social environments in the foreseeable future. An ideal sustainable society would be one in which all energy would be derived from current solar income and all non-renewable resources would be recycled." (pp10-11)

Porritt (1984) - Director, U.K. Friends of the Earth

1. "All economic growth in the future must be **sustainable**: that is to say, it must operate within and not beyond the finite limits of the planet." (p120)

Repetto (1985a) - economist, World Resources Institute. Also in Repetto (1986a), pp16-17

1. "The core of the idea of **sustainability**, then, is the concept that current decisions should not impair the prospects for maintaining or improving future living standards. ... This implies that our economic systems should be managed so that we live off the dividend of our resources, maintaining and improving the asset base. This principle also has much in common with the ideal concept of income that accountants seek to determine: the greatest amount that can be consumed in the current period without reducing prospects for consumption in the future." (p10)
2. "This does not mean that **sustainable development** demands the preservation of the current stock of natural resources or any particular mix of human, physical and natural assets. As development proceeds, the composition of the underlying asset base changes." (p10)
3. "There is broad agreement that pursuing policies that imperil the welfare of future generations, who are unrepresented in any political or economic forum, is **unfair**." (p11)

Redclift (1987) - academic economist

1. "...to what extent is economic growth an adequate measure of development?" (p15)

Solow (1986) - Nobel Prize academic economist

1. "...a society that invests in reproducible capital the competitive rents on its current extraction of exhaustible resources, will enjoy a **consumption stream constant in time**. ...this result can be interpreted as saying that an appropriately defined stock of capital - including the initial endowment of resources - is being maintained intact, and that consumption can be interpreted as the interest on that patrimony." (p141).

Talbot (1984) - former Director-General, IUCN

1. "OBJECTIVES OF THE WORLD CONSERVATION STRATEGY

Conservation has three basic objectives:

- (1) To maintain essential ecological processes and life support systems.
- (2) To preserve genetic diversity.
- (3) To ensure that the utilization of living resources, and the ecosystems in which they are found, is **sustainable**." (p4)

Tietenberg (1984) - academic economist

1. "The sustainability criterion suggests that, at a minimum, future generations should be left no worse off than current generations." (p33)
2. "Rather than eliminating the [positive] discount rate, the present-value criterion should be complemented by other criteria, such as sustainability.For example, we might choose to maximise present value subject to the constraint that future generations are not made worse off". (p432)

Tolba (1987) - Executive Director, U.N. Environmental Programme.

1. "[Sustainable development] has become an article of faith, a shibboleth: often used but little explained. Does it amount to a strategy? Does it apply only to renewable resources? What does the term actually mean? In broad terms the concept of sustainable development encompasses:

- (1) help for the very poor because they are left with no option other than to destroy their environment;
- (2) the idea of self-reliant development, within natural resource constraints;
- (3) the idea of cost-effective development using different economic criteria to the traditional approach; that is to say development should not degrade environmental quality, nor should it reduce productivity in the long run;
- (4) the great issues of health control, appropriate technologies, food self-reliance, clean water and shelter for all;
- (5) the notion that people-centred initiatives are needed; human beings, in other words, are the resources in the concept." (p98)

Tonn (1988)

1. "Two principles of 500-year planning:

Principle 1: Future generations should not inherit, from present generations, unacceptable risks of death owing to environmental or other preventable catastrophes.

Principle 2: Future, as well as present, generations may inherit constraints on their primary freedoms as sacrifices for enjoying the conditions of Principle 1." (6th page of article)

Turner - academic economist

1. "The World Conservation Strategy...gave considerable prominence to the sustainability concept, although its precise meaning and practical applications were not presented in a detailed and operational form." (1987, p576)
2. "The precise meaning of terms such as 'sustainable resource usage', 'sustainable growth' and 'sustainable development' has so far proved elusive." (1988, p5).
3. "In principle, such an optimal [sustainable growth] policy would seek to

maintain an 'acceptable' rate of growth in per-capita real incomes without depleting the national capital asset stock or the natural environmental asset stock." (1988, p12)

4. "It makes no sense to talk about the **sustainable use of a non-renewable resource** (even with substantial recycling effort and reuse rates). Any positive rate of exploitation will eventually lead to exhaustion of the finite stock." (1988, p13)

5. "...in this [**sustainable development**] mode...conservation becomes the sole basis for defining a criterion with which to judge the desirability of alternative allocations of natural resources." (1988, p21).

WCED (1987) [Brundtland Report]

1. "We came to see that a new development path was required, one that sustained human progress not just in a few places for a few years, but for the entire planet into the distant future. Thus '**sustainable development**' becomes a goal not just for the 'developing' nations, but for industrial ones as well." (p4)

2. "**Sustainable development** is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:

- o the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and
- o the idea of limitations imposed by the state of technology and social organisation on the environment's ability to meet present and future needs." (p43)

3. "Even the narrow notion of **physical sustainability** implies a concern for social equity between generations, a concern that must logically be extended to equity within each generation." (p43)

4. "Living standards that go beyond the basic minimum are sustainable only if consumption standards everywhere have regard for long-term sustainability. Yet many of us live beyond the world's ecological means, for instance in our patterns of energy use. Perceived needs are socially and culturally determined, and **sustainable development** requires the promotion of values that encourage consumption standards that are within the bounds of the ecological possible and to which all can reasonably aspire." (p44)

5. "Economic growth and development obviously involve changes in the physical ecosystem. Every ecosystem everywhere cannot be preserved intact." (p45)

6. "The loss [i.e. extinction] of plant and animal species can greatly limit the options of future generations; so **sustainable development** requires the conservation of plant and animal species." (p46)

World Bank

1. "...satisfy the multiple criteria of **sustainable growth**, poverty alleviation, and sound environmental management." (1987, p10)
2. "To a large degree, environmental management should be seen as a means of attaining the wider objectives of **sustained economic growth** and poverty alleviation." (1987, p18)
3. "...elevating concern about environmental matters...and developing the capacity to implement sound practices for environmental management...are [both] needed to reconcile, and, where appropriate, make tradeoffs among the objectives of growth, poverty alleviation, and sound environmental management." (1987, p28)

ASSERTIONS OF ECONOMY-ENVIRONMENT INTERACTIONS

Allen (1980) - summarising IUCN (1980)

3. "development.... **depends** upon conservation, and that conservation **depends** equally upon development." (p9)
4. "conservation of the biosphere is a prerequisite for human survival and well-being; ...**interdependence** is an inescapable fact of life." (p16)

Bartelmus (1986)

1. "...the overall goals of environment and development are not in conflict but are indeed the same, namely the improvement of the human quality of life or welfare for present and future generations." (pp13-14)

Clark (1986) - environmental scientist and policy analyst, IIASA

2. "Throughout most of history, the interactions between human development and the environment have been relatively simple and local affairs. But the complexity and scale of these interactions are increasing. ... What were once straightforward questions of ecological preservation versus economic growth now reflect **complex linkages** - witness the **feedbacks** among energy and crop production, deforestation and climatic change that are evident in studies of the atmospheric 'greenhouse' effect." (p5)

Tolba (1987) - Executive Director, UNEP

2. "...economic development and environmental quality are **interdependent** and, in the long term, mutually reinforcing. The rational management of the world's threatened natural resource base forestalls a loss in environmental quality and enhances sustainable economic growth." (p150)

WCED (1987)

7. "...it is **impossible to separate** economic development issues from environment issues; many forms of development erode the environmental resources upon which they must be based, and environmental degradation can undermine economic development. Poverty is a major cause and effect of global environmental problems." (p3)

World Bank

4. "Promoting growth, alleviating poverty, and protecting the environment are **mutually supportive** objectives in the long run. ... In the short run, however, the objectives are not always compatible..." (1987, p5)

5. "Poverty - of people and of countries - is thus a major cause of environmental degradation. That makes it essential, if environmental degradation is not to become completely unmanageable, to devise policies oriented toward economic growth, with special emphasis on improving the incomes of the poor. ... Nevertheless economic growth may also destroy the environment and further jeopardize the already tenuous lives of the poor. ... Thus, although growth is imperative for alleviating poverty, it may also adversely affect the poor and the environment if inadequate attention is paid to the poor and their needs." (1987, pp6-7)

6. "...economic growth, the alleviation of poverty, and sound environmental management are in many cases mutually consistent objectives." (1988, p1)

APPENDIX 2 CAKE-EATING MODEL WITH NO ENVIRONMENTAL EFFECTS

The following example analyses a cake-eating economy, with exogenous technological progress in consuming ("eating") a non-renewable natural resource ("cake") and a large number N of economically identical agents who have explicit, purely materialistic preferences. This economy is derived from a more general model in Krautkraemer (1985). There are no "environmental" effects on agents' utility functions or on the cake-eating process, although the dependence of consumption on eating into a finite, non-renewable cake is clearly a natural resource constraint. Intertemporal preferences are assumed to be dynamically consistent, so that the utility discount rate δ is a constant, as shown by Strotz (1956). See Figure 7 for illustration.

Each agent is assumed to eat into his personally-owned stock of cake $s(t)$ (dropping the subscript n for non-renewable) so as to maximise the present discounted value of utility over an infinite time horizon, i.e. to choose

$$s^*(t) \text{ to maximise } \int_0^{\infty} u[c]e^{-\delta t} dt, \text{ where}$$

- s = per capita stock of non-renewable natural resource
- u = per capita utility
- c = per capita consumption
- δ = utility discount rate, > 0
- t = time

$$u[c] = c^{\nu}, \quad 0 < \nu < 1 \text{ (this ensures the diminishing marginal utility of consumption)}$$

$$c = -\dot{s}e^{\tau t} \text{ (a rudimentary production function, assuming exogenous technological progress in "cake-eating" at a constant rate } \tau > 0)$$

$$c \geq 0 \text{ and } s \geq 0, \quad \forall t > 0 \text{ (non-negativity constraints)}$$

$$s(0) = s_0 > 0 \text{ (initial condition).}$$

Using Euler's equation, the differential equation for the individually optimal time path of the resource stock $s^*(t)$ is then:

$$\ddot{s}s + [(\delta - \tau\nu)/(1 - \nu)]\dot{s}s = 0$$

which has the following solution:

$$s^*(t) = s_0 e^{-\phi t}, \quad c^*(t) = \phi s_0 e^{(\tau - \phi)t}, \quad u^*(t) \propto e^{(\tau - \phi)\nu t}$$

where $\phi = (\delta - \tau\nu)/(1 - \nu)$ and hence $(\tau - \phi) = (\tau - \delta)/(1 - \nu)$

Hence there are two cases here (assuming that $\delta > \tau\nu$ for convergence)

- A $\underline{\delta \leq \tau}$. In this case the optimal path has $\dot{u} \geq 0$, i.e. is "sustainable".
- B $\underline{\delta > \tau}$. In this case the optimal path has $\dot{u} < 0$, and so is unsustainable.

APPENDIX 3 CAKE-EATING WITH ENVIRONMENTAL AMENITY OR PRODUCTIVITY

This model shows a very simple example of how environment/economy interactions can alter the simple cake-eating model of Appendix 2 and make it less sustainable. We use specific functional forms for the interactions, so the results are not general, but nevertheless quite suggestive.

Suppose: either that that the utility function is $u = c^\nu S^\epsilon$ instead of $u = c^\nu$,

where $S = Ns$ is the total stock of the natural resource, which now has both direct amenity value as well as productive uses, and S^ϵ ($\epsilon > 0$) is the new environmental amenity term, as shown in Figure 8;

or that production function is $c = -S^{\epsilon/\nu} \dot{s} e^{\tau t}$ instead of $c = -\dot{s} e^{\tau t}$,

with $S^{\epsilon/\nu}$ as the environmental productivity term, as in Figure 9.

Either way - this particular example does not actually distinguish between amenity and productivity effects - the optimisation (present value maximisation) problem for any individual becomes:

$$\text{find } s^*(t) \text{ to maximise } \int_0^\infty (-\dot{s})^\nu S^\epsilon e^{(\tau\nu - \delta)t} dt \quad (\text{notation as in Appendix 2})$$

(Assume that $\delta > \tau\nu$ for convergence of this integral; also require $\nu + \epsilon < 1$.)

We assume that the economy comprises a large number N of identical non-cooperating individuals, who act as if $\partial S/\partial s = 0$: this non-cooperation is crucial in generating nonoptimal depletion of the environmental resource. Using Euler's equation, the differential equation for the optimal time path of the resource stock $s^*(t)$ can then be shown to be:

$$\ddot{s} s^* - [\epsilon/(1-\nu)](\dot{s}^*)^2 + [(\delta - \tau\nu)/(1-\nu)]\dot{s}^* s^* = 0$$

which has the following solution:

$$s^*(t) = s_0 e^{-\psi t}, \quad c^*(t) = \psi s_0 e^{(\tau - \psi)t},$$

$$u^*(t) \propto e^{\nu(\tau - \psi)t} e^{-\epsilon\psi t} = e^{[\nu(\tau - \delta(1 + \epsilon/\nu))/(1 - \nu - \epsilon)]t}$$

where $\psi = (\delta - \tau\nu)/(1 - \nu - \epsilon) > \phi$; hence this non-cooperative solution is sustainable if and only if

$$\tau > \delta(1 + \epsilon/\nu) > \delta.$$

We can also show that the requirement for convergence of the utility integral, $\dot{u}^*/u^* < \delta$ is equivalent to $\delta > \tau\nu$, which then ensures that $\partial(\dot{u}^*/u^*)/\partial\epsilon < 0$. That is, utility growth is reduced by a stronger environmental effect ϵ , and a higher minimum rate of technical progress is required to just achieve sustainability in this case than in the purely materialist model in Appendix 2 above. On the other hand the social optimum, which would be achieved if individuals behaved cooperatively as if $\partial S/\partial s = N$, has a differential equation

$$\ddot{s}^*s^* + (\varepsilon/\nu)(\dot{s}^*)^2 + [(\delta - \tau\nu)/(1-\nu)]\dot{s}^*s^* - 0$$

which has the following solution:

$$s^*(t) = s_0 e^{-\theta t}, \quad c^*(t) = \theta s_0 e^{(\tau - \theta)t},$$

$$u^*(t) \propto e^{\nu(\tau - \theta)t} e^{-\varepsilon\theta t}, \quad \dot{u}^*/u^* = \nu\tau - (\nu + \varepsilon)\theta = \nu(\tau - \delta)/(1 - \nu)$$

where $\theta = \nu(\delta - \tau\nu)/[(1-\nu)(\nu + \varepsilon)] < \phi$; hence this social optimum solution is sustainable if and only if $\tau > \delta$, as in Appendix 2.

There are thus three policy cases here, illustrated in Figure 10, with Case A of Appendix 2 now split into two sub-cases. (We expect this threefold classification to apply to many "tragedies of the commons" cases where externalities and non-cooperative behaviour lead to a nonoptimal profile of resource depletion.)

- A1 If $\delta \leq \tau/(1 + \varepsilon/\nu)$, the non-cooperative path is of course nonoptimal but has $\dot{u} \geq 0$, i.e. is "sustainable".
- A2 If $\tau/(1 + \varepsilon/\nu) < \delta \leq \tau$, the non-cooperative path is both nonoptimal and has $\dot{u} < 0$, i.e. is unsustainable, while the socially optimal path is sustainable.
- B If $\delta > \tau$, both the non-cooperative and socially optimal paths have $\dot{u} < 0$, i.e. are unsustainable.

What sort of policy options are available to achieve sustainability in our simple cake-eating economy? Solow (1974a, p12) suggests a policy solution of resource conservation subsidies, or of severance (resource depletion) taxes that fall through time. Still assuming economically identical, non-cooperative agents, consider therefore the effect of government conservation subsidies first, applied in a zero-revenue form. Assuming that agents do not cooperate (i.e. make a zero conjectural variation), this means that the individual perceives an increased incentive to conserve resources while the government's budget remains balanced.

A zero-revenue resource conservation subsidy applied at rate σ thus changes an agent's perception of the cake-eating relationship

$$\text{from } \dot{s} = -ce^{-\tau t} \quad \text{to } \dot{s} = -ce^{-\tau t} + \sigma(s - S/N)$$

Here the total resource stock $S = Ns$ in aggregate, but an agent acts as if $\partial S/\partial s = 0$ (we are assuming N is so large that an agent even ignores the effect that his own stock depletion actually has on the total stock S). This then can be shown to transform the differential equation for the optimal stock path $s^*(t)$ to

$$\ddot{s}^*s^* - [\varepsilon/(1-\nu)](\dot{s}^*)^2 + [(\delta - \sigma - \tau\nu)/(1-\nu)]\dot{s}^*s^* - 0$$

which has solution

$$s^*(t) = s_0 e^{-\psi' t}; u^*(t) \propto (\psi')^\nu e^{[(\tau - \psi')\nu - \psi' \epsilon] t} \text{ where } \psi' = (\delta - \sigma - \tau\nu)/(1 - \nu - \epsilon)$$

and hence $\dot{u}^*/u^* = (\tau - \psi')\nu - \psi' \epsilon = [\tau\nu - (\delta - \sigma)(\nu + \epsilon)]/(1 - \nu - \epsilon)$.

Therefore, to just achieve sustainability ($\dot{u} = 0$) we need a subsidy rate

$$\sigma_{\text{sus}} = \delta - \tau/(1 + \epsilon/\nu) > \delta - \tau;$$

whereas to achieve optimality $s^* = s_0 e^{-\theta t} = s_0 e^{-\nu(\delta - \tau\nu)t/[(1 - \nu)(\nu + \epsilon)]}$ we need

$$\psi' = \theta, \text{ i.e. } \sigma_{\text{opt}} = (\delta - \tau\nu)/[(1 + \nu/\epsilon)(1 - \nu)], > 0 \text{ if and only if } \delta > \tau\nu.$$

Note that when $\delta = \tau$ we have $\sigma_{\text{sus}} = \sigma_{\text{opt}}$, as expected since then the optimal solution is just sustainable.

It can be shown that Solow's alternative suggestion of a zero-revenue resource depletion tax, at a proportional rate $\lambda(t)$, can be related to the privately optimal path $s^*(t)$ by:

$$\dot{\lambda}(t)/[\lambda(t) - 1] = (1 - \nu)\dot{s}^*/s^* - (\tau\nu - \delta).$$

So to get $s^* = s_0 e^{-\tau\nu t/(\nu + \epsilon)}$, i.e. just sustainable we need

$$\begin{aligned} \dot{\lambda}(t)/[\lambda(t) - 1] &= -(1 - \nu)\tau\nu/(\nu + \epsilon) - (\tau\nu - \delta) \\ &= \delta - \tau(1 + \epsilon)/(1 + \epsilon/\nu) \end{aligned}$$

$$\text{i.e. } \lambda_{\text{sus}}(t) = 1 - k_0 e^{[\delta - \tau(1 + \epsilon)/(1 + \epsilon/\nu)]t}, \quad k_0 \text{ some constant}$$

and to get $s^* = s_0 e^{-\theta t}$, i.e. optimal we need

$$\dot{\lambda}(t)/[\lambda(t) - 1] = (\delta - \tau\nu)/(1 + \nu/\epsilon)$$

$$\text{i.e. } \lambda_{\text{opt}}(t) = 1 - k_0 e^{(\delta - \tau\nu)t/(1 + \nu/\epsilon)}, \quad k_0 \text{ some constant}$$

Note how the depletion tax rate falls over time and may eventually become a depletion subsidy; the time profile of the tax rate is what matters.

Interpretation in terms of sustaining the resource base

We can interpret the above results in terms of maintaining the "effective resource base". The remaining value of the cake resource at time t here is

$$\begin{aligned} V(t) &= \int_0^1 (S e^{\tau t})^\nu (xS)^\epsilon dx \quad \text{in the environmental amenity case} \\ &= \int_0^1 (S e^{\tau t} [xS]^{\epsilon/\nu})^\nu dx \quad \text{in the environmental productivity case} \end{aligned}$$

Both integrals are of course the same. Sustaining the effective resource base requires that $V \geq 0$, i.e. $S^{1 + \epsilon/\nu} e^{\tau t}$ does not decline,

$$\text{i.e. } \dot{S}/S \geq -\tau/(1 + \epsilon/\nu)$$

which is same as the condition above for sustainability.

APPENDIX 4 CAPITAL ACCUMULATION WITH ENVIRONMENTAL AMENITY OR PRODUCTIVITY

The two models here are adaptations from Stiglitz (1974). They differ from Appendix 3 by introducing a production function requiring inputs of capital and labour, as well as the non-renewable resource flow $R (= -dS/dt)$, in order to produce output Q . (For simplicity we continue to assume that population L is constant.) The first model has multiplicative environmental amenity and a Cobb-Douglas production function with exogenous technological progress:

$$\begin{aligned} \text{Utility} \quad & u = c^\nu S^\epsilon && 0 < \nu, \epsilon < 1 \\ \text{Output} \quad & Q = AK^\alpha L^\beta R^\gamma e^{\tau t} && 0 < \alpha, \beta, \gamma < 1; \alpha + \beta + \gamma = 1; \tau > 0 \end{aligned}$$

(see Figure 12 for illustration of this model). The second has no amenity but multiplicative environmental productivity, so that output is affected not only by the resource flow R but also by the resource stock S :

$$\begin{aligned} \text{Utility} \quad & u = c^\nu && 0 < \nu < 1 \\ \text{Output} \quad & Q = AK^\alpha L^\beta R^\gamma S^\pi e^{\tau t} && 0 < \alpha, \beta, \gamma, \pi < 1; \alpha + \beta + \gamma = 1; \tau > 0 \end{aligned}$$

Note that the second production function is assumed to have increasing returns to scale. This is to avoid interdependencies between parameters that would arise if we were to require that $\alpha + \beta + \gamma + \pi = 1$. The methodology is as in Stiglitz. It is not possible to give a general analytical solution, and so we look at possible steady state solutions which assume that all stocks and flows have constant (positive or negative) growth rates. We can then work in simple linear equations of growth rates defined as

$$g\langle x \rangle \text{ or } g_x = \dot{x}/x$$

Thus for the environmental amenity model we have:

$$g\langle u_c \rangle = -(1-\nu)g_c + \epsilon g_S \quad \text{where of course } g_S = -R/S$$

$$g_Q = \alpha g_K + \gamma g_R + \tau$$

$$g_K = Q/K - C/K \quad (\text{output not consumed leads to capital growth})$$

$$Q_K - \delta = -g\langle u_c \rangle \quad (\text{Ramsey rule: excess of interest rate over utility discount rate compensates for declining marginal utility})$$

$$g\langle Q_R \rangle = Q_K \quad (\text{Hotelling rule: resource price rises at the rate of interest})$$

For the environmental productivity model the first two equations are changed:

$$g\langle u_c \rangle = -(1-\nu)g_c$$

$$g_Q = \alpha g_K + \gamma g_R + \pi g_S + \tau$$

The fact that agents are non-cooperative, and therefore ignore the public environmental value of the total resource stock S , is reflected in the mathematics by using the standard Hotelling rule to determine the resource depletion rate. On the socially optimal path, the Hotelling rule should be modified to account for the social environmental value of the resource. Solving these linear equations gives the following results for the privately optimal (non-cooperative) paths:

Environmental amenity model (environmental parameter is ϵ)

$$\begin{aligned} \text{Optimal resource depletion rate} \quad -g_S &= \frac{\delta(1-\alpha) - \tau\nu}{[\beta + (1-\nu)\gamma - \epsilon(1-\alpha)]} \\ \text{Optimal real interest rate} \quad \alpha Q/K &= \frac{\tau(1-\nu-\epsilon) + \beta\delta}{\alpha[\beta + (1-\nu)\gamma - \epsilon(1-\alpha)]} \\ \text{Optimal growth rate of utility} \quad g_u &= \frac{\nu(\tau-\gamma\delta) - \epsilon(1-\alpha)\delta}{[\beta + (1-\nu)\gamma - \epsilon(1-\alpha)]} \end{aligned}$$

It is interesting to determine the effect of varying the environmental parameter ϵ in these paths. First note that, for the above solutions to be meaningful, the integral of discounted utility (which our optimal control procedure is maximising) must converge. This requires that the discount rate δ must be greater than the above optimal growth rate of utility g_u , which after some manipulation means that

$$\delta(\beta+\gamma) > \nu\tau$$

Note that (provided always that $\tau > 0!$) this justifies a positive discount rate, since a zero discount rate would lead to perpetual saving and current impoverishment, as Olson and Bailey (1981) have pointed out. Differentiating the three optimal growth rates with respect to ϵ then gives

$$\partial(-g_S)/\partial\epsilon > 0$$

$$\partial(\alpha Q/K)/\partial\epsilon \propto \delta(\beta+\gamma) - \nu\tau > 0$$

$$\partial g_u/\partial\epsilon \propto \nu\tau - \delta(\beta+\gamma) < 0$$

Environmental productivity model (environmental parameter is π)

$$\begin{aligned} \text{Optimal resource depletion rate} \quad -g_S &= \frac{\delta(1-\alpha) - \tau\nu}{[\beta + (1-\nu)\gamma - \pi\nu]} \\ \text{Optimal real interest rate} \quad \alpha Q/K &= \frac{\tau(1-\nu) + (\beta-\pi)\delta}{\alpha[\beta + (1-\nu)\gamma - \pi\nu]} \end{aligned}$$

Optimal growth rate of utility
$$g_u = \frac{\nu[\tau - \delta(\gamma + \pi)]}{[\beta + (1-\nu)\gamma - \pi\nu]}$$

Convergence of discounted utility $\rightarrow \delta(\beta + \gamma) > \nu\tau$ again

Response of optimal paths to change in environmental parameter π :

$$\partial(-g_S)/\partial\pi > 0$$

$$\partial(\alpha Q/K)/\partial\pi \propto \nu\tau - \delta(\beta + \gamma) < 0$$

$$\partial g_u/\partial\pi \propto \nu\tau - \delta(\beta + \gamma) < 0$$

With proportional conservation subsidy σ but no environmental effects:

The Hotelling rule is modified to $g_{Q_R} = Q_K/(1+\sigma)$ with results:

Optimal resource depletion rate
$$-g_S = \frac{\delta(1-\alpha) - \tau(\nu + \sigma)}{[\beta(1+\sigma) + (1-\nu)\gamma]}$$

Optimal interest rate
$$\alpha Q/K = \frac{\tau(1-\nu) + \beta\delta}{\alpha[\beta + (1-\nu)\gamma/(1+\sigma)]}$$

Optimal growth rate of utility
$$g_u = \frac{\nu[\tau(1+\sigma) - \gamma\delta]}{[\beta(1+\sigma) + (1-\nu)\gamma]}$$

Assume for utility convergence that $\delta[\beta + \gamma/(1+\sigma)] > \nu\tau$; note that a lower discount rate is required for convergence thanks to $\sigma > 0$.

Response of optimal paths to change in subsidy rate σ :

$$\partial(-g_S)/\partial\sigma \propto -\tau(1-\nu) - \beta\delta < 0$$

$$\partial(\alpha Q/K)/\partial\sigma > 0$$

$$\partial g_u/\partial\sigma \propto \tau(1-\nu) + \beta\delta > 0$$

Results with both environmental effects and conservation incentives still have to be computed.

APPENDIX 5 CORN-EATING WITH A MINIMUM SUBSISTENCE LEVEL

In this model population N grows exponentially at a constant, exogenous rate λ , and is supported by the harvest from a single, renewable resource S ("corn"). Capital, non-renewable resources and labour inputs are ignored. There is a minimum subsistence level of consumption c_m below which life is not worth living, and the utility function is purely materialistic:

$$u \propto (c - c_m)^\nu, \quad c_m > 0, \quad 0 < \nu < 1;$$

The resource has no public amenity value. See Figure 13 for illustration.

The resource stock S grows naturally at exponential rate ρ , but is also eaten by people at rate C , with no technical progress in the consumption process:

$$\dot{S} = \rho S - C, \quad \text{so that} \quad \dot{S}/S = \rho - C/S$$

Since the resource clearly has a productivity value, we are assuming private ownership of the resource to avoid any nonoptimality caused by open access. Converting to per capita resource stock $s = S/N$ and consumption $c = C/N$:

$$\dot{S}/S = \dot{s}/s + \dot{N}/N = \dot{s}/s + \lambda, \quad \text{and} \quad C/S = c/s \quad (\text{initial stock } s(0) = s_0)$$

$$\therefore \dot{s}/s + \lambda = \rho - c/s$$

$$\therefore \dot{s} = (\rho - \lambda)s - c, \quad \rho, \lambda > 0.$$

Maximising discounted unweighted utility

Maximising discounted utility $\int_0^{\infty} u[c(t)]e^{-\delta t} dt$ can be shown to give the following differential equation for the optimal corn stock $s(t)$:

$$(1-\nu)\dot{s} + [\delta - \gamma(2-\nu)]\dot{s} + \gamma(\gamma-\delta)s = (\gamma-\delta)c_m \quad \text{where } \gamma = \rho - \lambda$$

This is a linear equation with solutions for per capita variables:

$$\text{Resource stock } s^*(t) = c_m/\gamma + (s_0 - c_m/\gamma)e^{\eta t} \quad \text{where } \eta = (\rho - \lambda - \delta)/(1-\nu)$$

$$\text{Consumption } c^*(t) = c_m + (\gamma - \eta)(s_0 - c_m/\gamma)e^{\eta t}$$

$$\text{Utility } u^*(t) = [(\gamma - \eta)(s_0 - c_m/\gamma)e^{\eta t}]^\nu$$

(It can be shown that we must have $\gamma > \eta$ for convergence of the utility integral, so we are assured that $\gamma - \eta > 0$). For consumption and utility to grow sustainably we need both that

$$\eta > 0 \rightarrow \rho > \lambda + \delta$$

and $s_0 > c_m/\gamma$.

If $\eta < 0$, c approaches c_m over time, in other words society is grinding along at subsistence level because it is too impatient (too high a δ) to allow sustainable growth in the resource base. In contrast, if $\eta > 0$ but $s_0 < c_m/\gamma$, consumption crashes to zero in a finite time. This is because the initial resource stock is too small for the population to be fed from resource growth, so that people are forced to eat resource capital ("seedcorn") with inevitably disastrous consequences.

Maximising discounted utility weighted by future population levels

We may instead weight future per capita utility levels by the number of people alive then, we maximise $\int_0^Z u[c(t)]e^{-(\delta-\lambda)t} dt$ and simply replace δ by $\delta-\lambda$ in the above results:

$$\eta' = (\rho - \delta) / (1 - \nu)$$

Sustainable growth now requires

$$\eta' > 0 \rightarrow \rho > \delta, \text{ a less stringent condition than before;}$$

and $s_0 > c_m/\gamma$, the same condition as before.

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