Environmental and Resource Economics: Some Recent Developments

PARTHA DASGUPTA* AND KARL-GÖRAN MÄLER**

**Faculty of Economics, University of Cambridge, UK*
***Beijer International Institute of Ecological Economics, Stockholm, Sweden*

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Abstract

We survey those recent developments in environmental and resource economics that have been prompted by a puzzling cultural phenomenon, where one group (usually natural scientists) sees in humanity's current use of Nature's services symptoms of a deep malaise, even while another group (usually economists) documents the fact that people today are on average better off in many ways than they had ever been (so why the gloom?). The developments surveyed here reconcile some of the claims and counter claims, by showing that the protagonists have frequently talked past one another. We show that some of the disagreements would be blunted if (i) use were made of a comprehensive measure of wealth to judge the performance of economies and (ii) possible irreversibilities in ecological damages were commonly acknowledged. Regional estimates of changes in wealth per capita are reported. Implications are drawn for the persistence of rural poverty in the world's poorest regions, even as they experience aggregate growth in GNP.

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1. The Evolving Agenda

If you were to browse among leading journals in environmental and resource economics, you would discover that a recurrent activity in the field has been to devise ways of valuing the constituents of Nature (Freeman III, 1993). A question that would occur to you is, why? Why should there be a special need to determine the worth of Earth's various resources? Why not rely on market prices?

The answer is that for many natural resources markets simply do not exist. In some cases they don't exist because the costs of negotiation and monitoring are too high, two broad categories being economic activities that are affected by ecological pathways involving long geographical distances (e.g., the effects of upstream deforestation on downstream activities many miles away) and those involving large temporal distances (e.g., the effect of carbon emission on climate, in a world where forward markets don't exist, because future generations are not present today to negotiate with us). Then there are natural assets (the atmosphere, aquifers, the open seas) for which the nature of the physical system (the migratory nature of the components of the assets) is such as to make it very difficult to define, let alone to enforce, property rights; a fact that keeps markets for such assets from existing. Ill-specified or unprotected property rights can also prevent markets from being formed (as is the case frequently with mangroves and coral reefs), while non-convexities in transformation possibilities among ecological goods and services would make markets function wrongly even if they *were* to form. In short, markets on their own aren't an adequate set of institutions for our relationships with Nature.

1.1 Institutional Externalities

We call those effects of human activities that occur without mutual agreement, *externalities*. Understandably, the study of externalities has greatly influenced the development of environmental and resource economics. Meade (1973), Mäler (1974), Baumol and Oates (1975), and Sandmo (2000) are book length accounts. However, these authors have shown that externalities are "epi-phenomena": they are not the real thing, but only manifestations of the real thing. Despite this commonly acknowledged insight, it is not uncommon to be told today that environmental and resource economics involves not much more than a study of externalities; which is rather like being told that the economics of asymmetric information involves not much more than a study of externalities. In fact, neither is to be told much. Interest in either subject arises when we ask *why* there are externalities and what forms they are likely to assume in various circumstances.

It is useful to classify externalities into two broad categories: *unidirectional* and *reciprocal* (Dasgupta, 1982). Damage inflicted by upstream deforestation on downstream farmers without compensation (Hodgson and Dixon, 1992), the acid rains that are inflicted on a region by another that is upwind (Mäler and de Zeeuw, 1998), and the spread of contagious diseases from infected to susceptible humans (Anderson and May, 1991; Ferguson *et al.*, 1997) are examples of the former; while the famous "tragedy of the commons" (Hardin, 1968) has become a metaphor for the latter. Excessive emissions into the atmosphere of carbon dioxide and the nitrogen oxides from industrial activity and modern transportation are examples of the tragedy; as is the reduced capacity for nitrogen fixation owing to changing land use (Steffen *et al*., 2004). Other instances where the tragedy occurs include unregulated fishing and groundwater withdrawal when there is free access to them.[1]

Economists have traditionally viewed externalities as symptoms of *market* failure. In consequence, optimal public instruments for the preservation of amenities, the control of pollution, and the extraction of natural resources in the face of market failure have been the broad subjects of enquiry in environmental and resource economics. Several previous surveys of the subject have reflected those preoccupations admirably (Fisher and Peterson, 1976, Cropper and Oates, 1992, Copeland and Taylor, 2004, on environmental pollution; and Brown, 2000, on renewable resources).

It has been appreciated for a long time, though, that non-market institutions (e.g., *communities*) frequently emerge in situations where markets either do not function well, or, in the extreme, do not exist. It has also long been appreciated that markets would not be able to operate extensively in the absence of a well-functioning State. But just as markets can malfunction, so can non-market institutions (including the State!) falter. An implication of the way we have defined externalities here is that they reflect *institutional failure*. One may say that environmental and resource problems are often symptoms of institutional failure, of which market failure is but one class of examples.

1.2 A Question and A Puzzle

With this background understanding, a question arises: In view of our dependence on the environment and natural resources, is contemporary economic development sustainable?

There is a remarkable divergence of opinion on the question, ranging from a straightforward "yes" to a flat "no". There is also the opinion that the question misleads, in that it is so aggregative as to suggest that environmental and (natural) resource conflicts are to be found only between "us" and a sequence of future "thems"; whereas, or so it is argued, large pockets of extreme poverty residing in what is otherwise an increasingly affluent world ensure that there are such conflicts even among contemporaries.

The environmental and resource problems facing a society are a function of its demand for goods and services. Population size contributes to that demand, but the average demand per person contributes to it too. Some people have argued that *per capita* consumption in industrialized nations have reached levels that are socially very costly and irresponsible, while others have claimed that high *per capita* consumption is essential if prosperity there is to be maintained and if poor countries are to prosper.

Underlying these intellectual tensions are the conflicting intuitions that have arisen from different empirical perspectives on whether the character of contemporary economic development, both in the poor world and in industrialized countries, is sustainable.[2] On the one hand, if we look at specific resources and services (fresh water, a wide variety of ecosystem services, and the atmosphere as a carbon sink), there is convincing evidence that continued growth in the rates at which they are utilized is unsustainable (Vitousek *et al*., 1986, 1997; Postel *et al*., 1996;

[1] Gordon (1954) was the first to analyse the implications of open access for a resource base. Scott (1955) is an original study on the effects of open access on fisheries, and Milliman (1956) is another on the effects on groundwater. For over four decades, the Prisoners' Dilemma game has been used by economists to show that a resource would be over-used under open access, but it was Hardin (1968) who popularised it by means of his admirable metaphor.

[2] For a good illustration of the conflicting intuitions, see the debate between Norman Myers and the late Julian Simon in Myers and Simon (1994).

Bolin, 2003; Steffen *et al*., 2004). For example, Vitousek *et al*. (1986) estimated that something like 40 percent of the net energy created by terrestrial photosynthesis (i.e., net primary production of the biosphere) is currently being appropriated for human use. This is of course a rough-and-ready figure; moreover, net terrestrial primary production isn't given and fixed: it depends in part on human activity. Nevertheless, the estimate does put the scale of the human presence on Earth in perspective. The figures also give us an idea of the unprecedented perturbation to the natural environment that has been created by human activity in a short space of time.[3]

On the other hand, if we study historical trends in the prices of marketed resources (e.g., minerals and ores), or the recorded growth in the conventionally measured indices of economic progress (such as gross national product (GNP) per head) in those countries that are today rich, environmental and resource scarcities would not appear yet to have bitten (Barnett and Morse, 1963; Simon, 1990; Johnson, 2000). World GNP *per capita* has grown three-fold (to over 5,000 US dollars) since the end of the Second World War; humans on average live some 20 years longer; and we are far better educated.

The new developments in environmental and resource economics we survey in this paper were a response to these conflicting intuitions. One of the achievements of that programme of research has been to establish that that particular disagreement can be resolved by abandoning indices of economic welfare that cover just the short run, such as GNP per head and the United Nations' Human Development Index (HDI)[4], and by adopting instead an inclusive measure of *wealth* (Sections 6-8). GNP per head (or, for that matter, HDI) can increase during an extended period, even while wealth per head declines. Studying trends in GNP per head, or HDI, can be misleading in regard to the economic prospects that may lie ahead. They could also mislead if we were to assess the past economic performances of nations solely in their terms (Section 6).

1.3 Resources and Pollutants

Natural resources are of direct use in consumption (fisheries), of indirect use as inputs in production (oil and natural gas), and of use in both (air and water). It may be that the value of a resource is derived from its usefulness (as a source of food, or as essential actors in enabling ecosystems to provide services - e.g., as keystone species), it may be that the value is aesthetic (places of scenic beauty), or it may be that it is intrinsic (primates, blue whales). In fact, the value may involve all three considerations (biodiversity). The worth of a resource could be from the value of what is extracted from it (timber), or from its presence as a stock (forest cover), or from both (watersheds). Interpreting natural resources in a broad way, as we are doing here, enables us to include on our list those assets that provide the many and varied ecosystem services upon which life is based. Those services include maintaining a genetic library, preserving and regenerating soil, fixing nitrogen and carbon, recycling nutrients, controlling floods, filtering pollutants, assimilating waste, pollinating crops, operating the hydrological cycle, and maintaining the gaseous composition of the atmosphere. A number have a global reach, but many are local. Nature's services are not only of direct value to us, they offer indirect benefits too: a multitude support and promote the natural resource base on which our economic activities are founded. Thus, for example, mangrove forests are not only sources of timber, but are also nursaries for wide varieties of fish populations. Moreover, they protect coastlines from storms, provide nutrients for aquatic life, and assimilate organic wastes that human populations deposit into the sea. (Naylor and Drew, 1998, show how one can elicit information concerning the value of a mangrove forest to those who are dependent on it.)

[3] This was the theme of a special symposium in *Science*, 1997, Vol. 277 (see especially the article by Vitousek *et al*.). See also McNeill (2000) for global statistics on changes in the magnitude of the perturbations that were made to the natural environment during the 20th century.

[4] HDI is a suitably normalised, linear combination of GNP per head, life expectancy at birth, and literacy (UNDP, 1990).

Ecosystems have close similarities with the interdependent economic systems that we economists study in the special circumstances of a general equilibrium: individual actors (whether organic or inorganic) interact with one another and generate ecosystem services (Mäler, 1974). Those interactions in the main involve *non-linear* dynamic processes. In Section 5 we illustrate by means of a simple model how such dynamic processes determine economic possibilities. Ehrlich *et al*. (1977), Daily (1997), Ehrlich and Ehrlich (1997), Levin (1999, 2001), Press *et al*. (2001), Gunderson and Holling (2002), and Steffen *et al*. (2004) contain extensive, authoritative accounts of the processes that yield Nature's services.

Pollutants are the reverse of natural resources. In some cases the emission of pollutants amounts directly to a degradation of ecosystems (the effect of acid rains on forests); while, in others, it means a reduction in environmental quality (deterioration of water quality), which also amounts to degradation of ecosystems (watersheds). Therefore, for analytical purposes, there is no reason to distinguish resource economics from environmental economics, or resource management problems from environmental management problems. Roughly speaking, "resources" are "goods" (in many situations they are the sinks into which pollutants are discharged), while "pollutants" (the degrader of resources) are "bads". If, over an extended period of time, the discharge of pollutants into an environmental sink exceeds the latter's assimilative capacity, the sink is destroyed (Section 5). Pollution is thus the reverse of conservation.[5] In what follows, the terms natural resources and the environment are used interchangebly.

1.4 Rural Poverty and the Local Resource Base

The above, expansive reading of the traditional terms *externalities*, *resources*, and *environment* has been invoked by a few economists in recent years to extend the reach of environmental and resource economics by investigating the numerous roles Nature plays in the lives of rural people in the world's poorest countries. This has led to the study of institutions that were created by the rural people to manage natural resources. (The focus on rural, as opposed to urban, poverty is understandable: some 60-70 percent of people in the world's poorest countries live in rural areas.) In studying Nature's roles in rural life and the rural institutions that have emerged to better meet those roles, investigators have drawn attention to *local* resource bases, which comprise such assets as ponds and streams, water holes and aquifers, swidden fallows and threshing grounds, woodlands and forests, grazing lands and village tanks, and fisheries and wetlands. They are for the most part *common property* and are frequently managed by *communitarian* institutions. Attempts have been made to uncover the pathways by which poverty and reproductive behaviour among rural people is linked to the state of their local resource base (Dasgupta, 1982, 1993, 2003a, 2004; Dasgupta and Mäler, 1991, 1995). Although the economics of development and environmental and resource economics have traditionally remained silent about each other (see, for example, the survey articles by Stern, 1989, on development economics; and by Cropper and Oates, 1992, and Brown, 2000, on environmental and resource economics, respectively), they are in fact closely related. You would not obtain a clear picture of rural life in the world's poorest regions if you were to neglect the direct role the local resource base plays there. And you would be unable to track the evolution of local resource bases in the world's poorest regions if you were to neglect the needs of the poor and the local institutions they managed to create in order to cope with those needs. We economists should not have expected matters to have been otherwise.

The study of local economies has drawn attention to the fact that, what counts in the ecology of rural life are populations of species: "species" *per se* is too broad a category. Thus, when wetlands, inland and coastal fisheries, woodlands, forests, ponds and lakes, and grazing fields are damaged (owing, say, to agricultural encroachment,

[5] Dasgupta (1982) develops the perspective in greater detail. See Heal (2000) for an application of the viewpoint to a watershed management problem in the Catskill Mountains in the state of New York.

or urban extensions, or the construction of large dams, or organizational failure at the village level, or resource usurpation by the State), traditional dwellers suffer. For them - and they are among the poorest in society - there are frequently no alternative source of livelihood, nor is migration usually an option. In contrast, for rich eco-tourists or importers of primary products, there is something else, often somewhere else, which means that there are alternatives. Whether there are substitutes for a particular resource is therefore not only a matter concerning technology and consumer preferences: the poor suffer from a lack of substitution possibilities in ways the rich don't.[6] Even the range between a need and a luxury is context-ridden. For these reasons environmental and resource economics needs not only to be inclusive in its recognition of what constitutes a capital asset, it needs also to be sensitive to individual and locational differences. A pond in one village is a different asset from a pond in another village, in part because their ecological characteristics differ, but in part also because the communities making use of them face different economic circumstances. In practice, of course, such refined distinctions may not be realizable in national income accounts; but it is always salutary to be reminded that macroeconomic reasoning glosses over the heterogeneity of Earth's resources and the diverse uses to which they are put - by people residing at the site and by those elsewhere. National income accounts reflect that reasoning by failing to record a wide array of our transactions with Nature.

1.5 Nature's Non-Convexities and Policy Failure

Earlier, we traced environmental and resource problems to institutional failure. But they can arise also from *policy failure*.

The catalogue of policy failures round the world that has been compiled over the years is long and varied. Some are reflections of corruption, vested interests, or sheer ineptitude; but there are examples of policy failure that can be interpreted as being inadvertent. For example, in an analysis of deforestation in the Brazilian Amazon, Alston *et al*. (1999) have argued that accelerated deforestation, followed by violent conflicts between landowners and squatters, has occurred because of legal inconsistencies between the civil law, which supports the title held by landowners, and the constitutional law, which supports the right of squatters to claim land not in "beneficial use" (e.g., farming or ranching). Ironically, the latter right reflects the government's stated desire for land reform. The authors have shown that the vagueness of the "use"-criteria and the uncertainty as to when a land owner's claim to a piece of land or a squatter's counter claim to it is enforced are together an explosive force.[7]

The political economy underlying policy failure has been much studied by economists, international agencies, and non-governmental organizations. By way of offering a contrast, we focus here on policy failures arising from the application of incorrect models of ecosystems. Theoretical studies on the optimum extraction of renewable resources and the policies that flow from them frequently assume that transformation possibilities among goods and services constitute convex sets. Convexity is a mathematically convenient assumption.[8] However, a large body of empirical

[6] For empirical confirmation of the links between resource degradation and the persistence of poverty, see Agarwal (1986), Cleaver and Schreiber (1994), Baland and Platteau (1997), Barbier (1997, 1999), Chopra and Gulati (1998), Aggarwal *et al*. (2001), Campbell *et al*. (2001), and Jodha (2001), among many others.

[7] In a wider discussion of the conversion of forests into ranches in the Amazon basin, Schneider (1995) has shown that the construction of roads through the forests has also been a potent force. Other examples of policy-induced environmental deterioration are the massive agricultural subsidies in the European Union. These are known to have encouraged agricultural practices harmful to aquatic ecosystems.

[8] For completeness, here is the definition of convexity *of a set*:
A commodity vector, say **z**, is a *convex combination* of commodity vectors **x** and **y** if **z** is a weighted average of **x** and **y**, where the weights are non-negative and sum to unity (that is, $\mathbf{z} = a\mathbf{x} + (1-a)\mathbf{y}$ for some $a \in [0,1]$). A set of commodity vectors is said to be *convex* if every convex combination of every pair of commodity vectors in the set is in the set. A set is *non-convex* if it is not convex.

studies by earth scientists has revealed that the pathways by which the constituents of ecosystems interact with one another and with the external environment frequently involve positive feedback. (See Steffen *et al*., 2004, for an illuminating set of studies.) The findings imply that the transformation possibilities among environmental goods and services, taken together, constitute non-convex sets. Nature's non-convexities are in many cases so significant, that to assume convexity there, even as an approximation, would be misleading (Section 5). For this reason, mathematical ecologists have studied the structural stability of ecosystems and the sizes and shapes of their basins of attraction for given sets of environmental parameters (May, 1977; Murray, 1993). Such notions as the *resilience* of ecosystems to withstand perturbations without siginificant changes in their character are expressions of this research interest (Perrings *et al*., 1995; Levin *et al*., 1998; Gunderson and Holling, 2002).[9]

Although non-convexities are prevalent in global ecosystems (ocean circulation, global climate), it is as well to emphasise the spatial character of many positive feedback processes. The latter have a direct bearing on rural people in the world's poorest regions. Eutrophication of ponds, salinization of soil, and biodiversity loss in a forest patch involve crossing ecological thresholds at a spatially localised level. Similarly, the metabolic pathways between an individual's nutritional status and his or her capacity to work, and those between a person's nutritional and disease status involve positive feedback.[10] Unfortunately, even applied studies frequently adopt linear approximations for modelling interrelationships involving non-convexities. Dose-response relationships between pollutants and their effects on human functionings are often taken to be linear, as are additional food and health-care requirements to combat widespread malnutrition (World Bank, 1993; UNDP, 2003).

There are further links between poverty and the non-convexities that people face. For the poor, to cross ecological thresholds can mean the foreclosure of substitution possibilities among resources, meaning that their range of options is non-convex. Studies of extreme poverty based on aggregation at the regional or national level can therefore mislead greatly.[11] The spatial confinement of many of the non-convexities inherent in Human-Nature interactions needs always to be kept in mind.

1.6 Institutions and Non-Convexities

The market mechanism is especially problematic in those situations where ecological pathways reflect significant non-convexities. It may prove impossible to decentralise an efficient allocation of resources by means exclusively of prices. Efficient mechanisms would involve additional social contrivances, such as (Pigovian) taxes and subsidies, quantity controls, social norms of behaviour, and so forth. Baumol and Bradford (1972) and Starrett (1972) observed that non-convexities are prevalent when losses traceable to environmental pollution are bounded. Starrett (1972) demonstrated that in the presence of such non-convexities, a competitive equilibrium simply does not exist: markets for pollution would be unable to equate demands to supplies. If the market price for pollution were negative (i.e., the pollutor has to pay the pollutee), pollutees' demand would be unbounded, while supply would be bounded. On the other hand, if the price were non-negative, demand would be zero, while supply, presumably, would be positive.[12]

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[9] Dasgupta and Mäler (2004) is a collection of technical articles on the economics of non-convex ecosystems.

[10] See Dasgupta (1993) for the relationship between nutritional status and human productivity, and for evidence on synergies between nutritional and disease status. An extensive set of references to the primary literature on these topics is also provided there.

[11] See the interchange between D. Gale Johnson (2001) and Dasgupta (2001b) on this.

[12] In an earlier classic, Arrow (1971) had observed that markets for externalities would suffer from another problem: no matter whether the externalities are positive or negative, the markets would be "thin", meaning that they would not be competitive.

The finding implied that private property rights to environmental pollution would not be capable of sustaining an efficient allocation of resources by means of the price system. However, Shapley and Shubik (1970) had already demonstrated by means of an example that if property rights are awarded to polluters, even such a non-price resource allocation mechanism as the core may not yield an outcome. The character of non-convexities is shaped not only by Nature, but also by human institutions (Starrett, 1973).

In his classic article, Starrett (1972) showed formally that a suitably chosen set of (Pigovian) pollution taxes, together with a system of competitive markets for other goods and services - assuming that the latter constitute a convex sector - would be capable of supporting an efficient allocation of resources. As there are no markets for pollution in such an allocation mechanism, the problem of equating supply to demand in pollution activities is bypassed. The moral would appear to be that social difficulties arising from the non-convexities can be overcome if the State were to assign property rights in a suitable way - permitting private rights to the convex sector, but reserving for itself the right to control emissions and discharges, be it directly in terms of regulations or indirectly by means of taxes and subsidies.[13]

1.7 Welfare Economics in an Imperfect State

Institutions falter everywhere. Communitarian institutions that evolved to manage local common property resources have been found to function effectively in some places, but examples abound where they have malfunctioned (Baland and Platteu, 1996). There are even places where trust among citizens has been so weak, that communitarian institutions have not involved members beyond the "family" (Banfield, 1958). As noted earlier, market failure is no uncommon phenomenon either.

It has been a common assumption in welfare economics, though, that the State operates effectively in those matters where other institutions falter. The assumption pervades *public economics*, which was developed for a society in which the State is not only trustworthy, but also optimizes on behalf of its citizens (Atkinson and Stiglitz, 1980; Myles, 1995). Policy prescriptions emerging from the theory are first-best (Utopian), or are at worst, second-best (Agathotopian; Meade, 1989). But such prescriptions are not self-evidently relevant for the world we have come to know; perhaps most especially for the majority of today's poor countries. In some places, the State is incompetent; in others it is predatory and vicious. It is hard to imagine the sense in which governments in what are demonstrably failed or predatory states may be said to be optimizing on behalf of their citizens.

However, it is not absurd to imagine that even in the most corrupt and predatory of governments, there are honest people. It can be safely assumed that such figures are only minor officials, involved in making marginal decisions (a road here, a local environmental protection plan there, and so on). What language does welfare economics have to speak to such people? What intellectual tools do they have for assessing whether the economic policies their governments are pursuing are likely to lead to *sustainable development*?

[13] Since the relative merits of regulations and taxes to curb pollution under asymmetric information have been much discussed in the published literature (Meade, 1973; Cropper and Oates, 1992), we ignore them here.

2. Plan of the Paper

This paper is not meant to be a survey of recent work in environmental and resource economics. Our aim is far more restricted. It is to offer an account of recent work that reconciles the conflicting intuitions mentioned in Section 1.2. That work was built on the questions, observations, and findings sketched in Sections 1.3-1.7. Each of the issues discussed there has been crucial for finding an answer to the question of how the honest decision maker we have just alluded to can best conduct policy analysis. We show how standard welfare economics can be adapted to enable the honest decision maker, even in the most dysfunctional of societies, to weigh the various considerations when deliberating over small policy changes. The formal language that is developed below can also be used in an informal way by the concerned citizen to reason about economic policies.

Each of the issues discussed in Sections 1.3-1.7 has also been crucial for constructing a formal language in which to determine whether economic development in a region, or among a group, has been sustainable. We will discover that, when our dependence on Nature's services is acknowledged, there is a strong element of "common sense" in economic reasoning. Paradoxes arise only when important factors of production are dismissed as being negligible.

We confine ourselves to theoretical developments. When required for the purpose of motivating or validating the theory, we describe applied work. But we do not elaborate on the applied work, nor do we evaluate it. Applied research has occasionally shaped the development of the theory reported here (e.g., an extensive literature on policy failures and the effects of civil disorder in many regions of the world), but it has on occasion also been prompted by it.[14] Unfortunately, applied research has all too often lagged behind economic theory. For example, we have found no more than a handful of publications in which a project involving ecological services has been evaluated comprehensively.[15] Studies estimating the value of environmental amenities abound in the published literature, but it is a rare publication that uses such estimates to conduct social cost-benefit analysis of projects involving those amenities. Moreover, macroeconomic forecasts rarely include environmental resources. Accounting for the environment, if it comes into the calculus at all, is an afterthought to the real business of "doing economics". To cite an example, the environment and natural resources made no appearance in the authors' assessment of what lies ahead in an influential, 38-page Survey of the World Economy in *The Economist* (25 September 1999). One can only assume that the authors took it as given that they are in unlimited supply.

On occasion, therefore, we report theoretical derivations even when we have no estimates of their orders of magnitude. We do so in order to encourage applied work. One of our motivations for preparing this survey has been to persuade professional colleagues that neglecting natural capital in studies of the long run can be hugely misleading. As a discipline, we would have been far ahead today in our understanding of the pathways that have shaped economic change in various regions of the world if growth and development economists had taken environmental and resource economics seriously in the past.

In Section 3, certain consequences of market imperfections in the use of natural resources are identified. Hidden subsidies in the export of primary products, paid for, possibly, by some of the world's poorest people, are identified. Biases in the direction of technological innovations are then discussed. One tentative conclusion we reach is that the more familiar types of market imperfections lead to an excessive use of natural resources.

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[14] See the pioneering works of Repetto *et al*. (1989), Vincent *et al*. (1997), and Lange *et al*. (2004) on the reconstruction of national accounts in Indonesia, Malaysia, and Southern Africa, respectively, by including changes in the stocks of natural capital. For some years now, the United Nations Statistical Office has been similarly engaged on an international scale.

[15] Anderson (1987) and Markandya and Murty (2004) are among the few.

Insights have been obtained by anthropologists, economists, and political scientists about resource management in rural regions of the world's poorest countries. Their work documents that communitarian institutions have often been successful in managing the local commons, but that at other times and places they have failed, or have broken down. Whether or not communitarian institutions are a success, there is a need to model their activities if public policies are to be evaluated. Section 4 is about communitarian institutions. The examples reported there suggest how they could be modelled for the purposes of understanding non-market allocation mechanisms guiding the use of environmental resources.

Section 5 studies an ecological process involving positive feedback. The example concerns phosphorus discharge into a shallow, fresh water lake. Close variants of the mathematical model of the shallow, fresh water lake have been used by ecologists and oceanographers to characterize diverse natural processes. We use the model to show that a prevailing view in the economics literature about environmental degradation, that it is mostly reversible, is misleading.[16]

Section 6 makes use of the findings in Sections 3-5 to develop welfare economics in imperfect economies. We are interested in two related questions there: (1) How should one evaluate policy reform (e.g., an investment project) in an imperfect economy? (2) How is one to check whether an economic forecast reflects sustainable development? We do not presume that the economy is convex, nor do we assume that the government optimizes on behalf of its citizens. We demonstrate first that, as in the case of first-best, convex economies, shadow prices are useful tools for economic evaluation. Sustainable development is then defined to be an economic programme along which intergenerational welfare does not decline. We show that the same set of shadow prices should be used both for policy evaluation and for assessing whether or not an economic forecast reflects sustained development. The wealth of a nation is the shadow value of its entire stock of capital assets, including not only manufactured capital, knowledge, and human capital, but also natural capital. We show that wealth, computed in terms of shadow prices, can be used as a criterion function for problem (1) and a numerical index for problem (2). The first result follows from the fact that the present discounted value of the flow of a project's shadow profits is the change in wealth at constant shadow prices. In other words, the well known criterion for project evaluation - choose a project if and only if the present discounted value of the flow of its social profits is positive - is really about changes to wealth brought about by investment projects.

The second result follows from the fact that an increase in wealth, at constant shadow prices, signals that intergenerational welfare is sustained during an interval of time. Therefore, at any moment of time, wealth increases if and only if *net* investment is positive. First-best, convex economies are shown to be an extreme special set of instances of the economies studied here.

Using the methods reported in Section 6, the way shadow prices can be estimated is explored in Section 7 by means of two examples. One concerns water extraction under free entry, while the other studies a polluted lake that is subject to a non-convex ecological process. The models developed in Sections 6-7 assume constant population and an absence of exogenous technological and institutional change. They also assume an absence of uncertainty. In Section 8 we relax those assumptions in turn and extend the equivalence result pertaining to changes in wealth and intergenerational welfare. Conditions under which wealth *per capita* could be used as an index of intergenerational welfare are derived; moreover, recent estimates of movements in wealth *per capita* in a number of countries are reported. In Section 9 we offer concluding remarks.

[16] The widespread appeal to the environmental Kuznets curve, publicised in World Bank (1992), is based on the idea that resource depletion is reversible.

3. Imperfect Markets

It is not uncommon today to interpret macroeconomic development in terms of the choices that are made by an optimising dynasty, facing perfectly competitive markets for goods and services (Blanchard and Fisher, 1989; Romer, 1996). Previously, such a view would have seemed puzzling. A large, post-War literature on intertemporal welfare economics sought to identify reasons why the economies we observe should not be expected to reflect optimum economic development. Three prominent reasons were identified: (1) imperfect capital markets; (2) imperfect risk markets; and (3) household myopia. Each can be shown to create a wedge between private and social rates of discount (see, for example, Arrow and Kurz, 1970; Lind, 1982; Arrow *et al*., 1996; Arrow *et al*., 2004).

Here we focus on the underpricing of environmental services. We study two examples to illustrate ways in which resource allocation can go astray when markets fail.

3.1 Structural Adjustment and the Natural Environment

People have criticized the way the World Bank-International Monetary Fund structural adjustment programmes were implemented in poor countries in the 1980s. Some have pointed to the additional hardship the poor have experienced in their wake. Others have argued that in order to reduce deficits, governments were led to embark on economic programmes that were particularly harsh on the natural resource base. Still others have argued that the two effects have come in tandem, that structural adjustment programmes encouraged countries to raise export revenue by depleting natural capital in a rapacious manner. On the other hand, proponents of structural adjustment programmes have argued that they encouraged the growth of markets and helped to reduce government deficits.

It is just possible that both proponents and opponents of the programmes were correct. The growth of markets and a reduction in government deficits benefit many, but, simultaneously, they can make vulnerable people face additional economic hardship. It is possible that the economic gains from structural adjustment were in principle large enough to compensate the losers, but losers frequently are not compensated; they may even remain undetected. There are a number of pathways by which this can happen. Here we sketch one.

An easy way for the State to earn revenue in countries endowed with forests is to issue timber concessions. The State can exercise its rights to forests that are public property by a judicious use of force to evict long-term dwellers. Timber concessions can then be sold to favoured firms, reducing government deficit, while simultaneously enlarging the private bank balances of officials. Forests are an easy target of usurpation by the State, because there tend to be no legal documents proving ownership.[17]

We leave aside the losses incurred by those evicted, because there is nothing really to say on the matter other than platitudes. It is more fruitful to think instead about concessions made on forests in the uplands of a watershed, so as to consider the ecological pathways by which deforestation inflicts damage on people in the lowlands (siltation, increased incidence of flooding, and so forth).[18] It pays to study them in terms of the assignment of property

[17] Colchester (1995) has recounted that political representatives of forest-dwellers in Sarawak, Malaysia, have routinely given logging licences to members of the state legislature. Primary forests in Sarawak are expected to be depleted within the next decade or so. Cruz and Repetto (1992) have described other pathways by which structural adjustment programmes have been unfriendly to the natural environment.

[18] The example is taken from Dasgupta (1990). Chichilnisky (1994) has developed the argument in the text in a more general context. Hodgson and Dixon (1992) is a case-study on logging and its impact on fisheries and tourism, in Palawan, the Philippines, that illustrates the example well.

rights. The common law in many poor countries, if we are permitted to use this expression in a universal context, recognizes pollutees' rights. So it is the timber merchant who, in principle, would have to compensate downstream farmers for the right to inflict the damage that goes with deforestation. However, even if the law sees the matter in this light, there is a gulf between the "written" law and the enforcement of law. When the cause of damage is hundreds of miles away, when the timber concession has been awarded to public land by the State, and when the victims are a scattered group of poor farmers or fishermen, the issue of a negotiated outcome doesn't usually arise. But when the timber merchant isn't required to compensate downstream farmers and fishermen, the private cost of logging is less than its social cost. Therefore, from the social point of view, we would expect excessive deforestation of the uplands. We would also expect that resource-based goods would be underpriced in the market (say, in export markets). The less roundabout is the production of the final good, the greater would this underpricing be, in percentage terms. Put another way, the lower is the value that is added to the resource in the course of production, the larger is the extent of this underpricing of the final product. The shadow price of timber being greater than its market price, there is an implicit subsidy on primary forest products, possibly on a massive scale. Moreover, the (export) subsidy is paid not by the general public via taxation, but by some of the most disadvantaged members of society (the sharecropper, the small landholder or tenant farmer, the fisherman). The subsidy is hidden from public scrutiny, which is why it isn't acknowledged officially. The hidden subsidy is a wealth transfer from the exporting country to the country that does the importing. We should be in a position to estimate such subsidies. As of now there are no such estimates.

3.2 Technological Biases

Such welfare indices as GNP per head are biased because they don't incorporate changes in the stocks of natural capital. The market price of natural resources on site is frequently zero, even though they are scarce goods. This means that commercial rates of return on investments that rely particularly on resources are higher than their social rates of return. Therefore, resource intensive projects appear better looking than they actually are. We would expect that, over time, an entire sequence of resource intensive technologies would be installed. Moreover, people learn by doing and learn by using, not only installed technology, but also in research and development. A large literature on technological change has shown that there is in consequence an element of path dependence in the development and use of new technology (Landau and Rosenberg, 1986; Dossi *et al*., 1988). The findings imply that modern technologies are not always appropriate technologies, but are often unfriendly towards those who depend directly on the local resource-base. The conclusion to be drawn poses a dilemma: it could be that we require a big push to move us away from our especial dependence on natural resources. Although empirical evidence is still scarce, the inappropriateness of installed technology is likely to be especially true in poor countries, where environmental legislations are frequently neither strong nor effectively enforced.

The transfer of technology from advanced countries can be inappropriate even when that same body of technology is appropriate in the country of origin. This is because shadow prices of natural resources, especially local resources, vary from country to country. A project-design that is socially profitable in one country may be socially unprofitable in another. This helps to explain why the poorest in poor countries, when permitted, have been known to protest against the installation of modern technology. It also helps to explain why environmental groups in poor countries not infrequently appear to be "backward-looking", trying to unearth traditional technologies for soil conversation, water management, forest protection, medical treatment, and so forth.[19] However, to do so isn't necessarily to assume an anti-science stance. Wrong prices can tilt the technological agenda in wrong directions.

[19] Agarwal and Narain (1996) is an interesting recent study in this vein.

One can presume that the bias toward resource-intensive technologies extends to the prior stage of research and development. When natural resources are underpriced, the incentives to develop technologies that would economize on their use are lower than what they should be. It follows that, once it is perceived that past choices have been especially damaging to the environment, cures are sought, whereas, prevention could well have been the better choice. Contemporary debates on the viability of carbon sequestration on a global scale is an illustration of this sequence of events.

4. Non-Market Institutions

Non-market institutions abound. In rural communities of poor countries, people rely on them for the purposes of obtaining credit and insurance, purchasing lumpy private goods (in what are called rotating savings and credit associations, or ROSCAs), and constructing and maintaining local public goods (terraces, shorelines, canals, and tanks). Non-market institutions supporting activities that involve the entire community (building and maintaining local public goods) are of a communitarian variety.

Natural resources in rural regions of poor countries are, in consequence, often communally owned. Not unoften, they are also communally managed. They are the *local commons*, comprising irrigation canals, tanks, water holes, threshing grounds, coastal fisheries, grazing fields, rivulets, and woodlands. As a proportion of total assets, the presence of local commons ranges widely across ecological zones. There is evidence from India that the commons are most prominent in arid regions, mountain regions, and unirrigated areas; they are least prominent in humid regions and river valleys (Agarwal and Narain, 1989; Chopra *et al*., 1990). This suggests that communal ownership enables the rural poor to pool risks more effectively than private ownership. Typically, the ownership is not "legal", but is instead, "historical". Whatever the source of the authority that underpins the ownership structure, the local commons are not open to outsiders: they are not "open access resources". Communal management is a frequent means by which the rural poor have tried to avoid the tragedy of the commons. A formal model of local commons, both when they are managed cooperatively and when not, was developed in Dasgupta and Heal (1979: Ch. 3). A large empirical literature has since developed, describing the many ingenious rules and regulations societies have devised in order to manage their local commons. (See Howe, 1986; Wade, 1988; Chopra *et al*., 1990; Feeny *et al*., 1990; Ostrom, 1990, 1992; Stevenson, 1991; Baland and Platteau, 1996; Beck and Nesmith, 2001; National Research Council, 2002; among many others.)

4.1 Importance of the Local Commons

Are the local commons important in people's lives? In a pioneering study, Jodha (1986) reported evidence from over 80 villages in 21 dry districts in India, that among poor families the proportion of income based directly on their local commons is in the range 15-25 percent. In a study of 29 villages in south-eastern Zimbabwe, Cavendish (2000) arrived at even larger estimates: the proportion of income based directly on the local commons is 35 percent, with the figure for the poorest quintile reaching 40 percent. Both investigators discovered in their samples that richer households drew a smaller proportion of their total income from the commons than poor households.

Communal management of local resources makes connection with social capital, viewed as a complex of interpersonal networks, and hints at the basis upon which cooperation has traditionally been built (Dasgupta, 1993, 2003b; Pretty and Ward, 2001). As the local commons have been seats of non-market relationships, transactions involving them are often not mediated by market prices. So their fate can go unreported in national economic accounts.

But there are wheels within wheels in communitarian relationships. In his work on South Indian villages, Seabright (1997) showed that milk producers' cooperatives are more prevalent in the drier districts there. But as the local commons are also more prevalent in drier districts, one way to interpret Seabright's finding is that cooperation in one sphere of life (managing the commons) makes cooperation in other spheres (marketing milk) that much easier: cooperation begets cooperation. The empirical literature on the local commons is valuable because it has unearthed how institutions that are neither part of the market system nor of the State develop organically to cope with resource allocation problems.

4.2 Weaknesses in Communal Ownership

Thus far, the good news about communitarian institutions. There are, however, two pieces of bad news. First, a general finding from studies on the management of local commons is that entitlements to products of the commons is frequently based on private holdings: richer households enjoy a greater proportion of the benefits from the commons. Beteille (1983), for example, drew on examples from India to show that access to the commons is often restricted to the elite (e.g., caste Hindus). Cavendish (2000) has reported that, in absolute terms, richer households in his sample took more from the commons than poor households. That women are sometimes excluded has also been recorded (e.g., from communal forestry; Agarwal, 2001).[20]

The second piece of bad news is that local commons have degraded in recent years in many parts of the poor world. Why should this happen now in those places where they had been managed in a sustainable manner previously?

One reason is deteriorating external circumstances, which lower both the private and communal profitability of investment in the resource base. There are many ways in which circumstances can deteriorate. Increased uncertainty in property rights are a prime example. You and your community may think that you together own the forest your forefathers passed on to you, but if you do not possess a deed to the forest, your communal rights are insecure. In a dysfunctional state of affairs, the government may confiscate the property. Political instability (in the extreme, civil war) is another source of uncertainty: your communal property could be taken away from you by force. Political instability is also a direct cause of environmental degradation: civil disturbance all too frequently expresses itself through the destruction of physical capital.

When people are uncertain of their rights to a piece of property, they are reluctant to make the investments necessary to protect and improve it. If the security of a communal property is uncertain (owing to whichever of the above reasons), the private returns expected from collective work on it are low. The influence would be expected to run the other way too, with growing resource scarcity contributing to political instability, as rival groups battle over resources. The feedback could be "positive", exacerbating the problem for a time, reducing private returns on investment further. Groups fighting over spatially localized resources are a frequent occurrence today (Homer-Dixon, 1999). Over time, the communitarian institutions themselves disintegrate.[21]

The second reason is rapid population growth, which can trigger resource depletion if institutional practices are unable to adapt to the increased pressure on resources. In Cte d'Ivoire, for example, growth in rural population

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[20] McKean (1992) stressed that benefits from the commons are frequently captured by the elite. Agarwal and Narain (1996) revealed the same phenomenon in their study of water management practices in a semi-arid village in the Gangetic plain.

[21] Recently de Soto (2000) has identified the absence of well-defined property rights and their protection as the central facts of underdevelopment. Rightly, he stressed the inability of poor people to obtain credit because of a lack of collateral. In the text we are offering a multi-causal explanation for poverty.

has been accompanied by increased deforestation and reduced fallows. Biomass production has declined, as has agricultural productivity (Lopez, 1998). Of course, rapid population growth in the world's poorest regions in recent decades itself requires explanation. Increased economic insecurity, owing to deteriorating institutions, is one identifiable cause: children are a fairly reliable form of capital asset (Bledsoe, 1994; Guyer, 1994; Heyser, 1996). To be sure, there are other causes, but even if rapid population growth is a proximate cause of environmental destruction, the underlying cause would be expected to lie elsewhere. Thus, when positive links are observed in the data between population growth, environmental degradation, and poverty, they should not be read to mean that one of them is the prior cause of the others. Over time, each could in turn be the cause of the others. (For the theory, see Dasgupta, 1993, 2003a; for a recent empirical study on South Africa that tests the theory, see Aggarwal *et al*., 2001.)

The third reason is that management practices at the local level have been known on occasion to be overturned by central fiat. A number of states in the Sahel imposed rules that in effect destroyed communal management practices in the forests. Villages ceased to have the authority to enforce sanctions on those who violated locally-instituted rules. State authority damaged local institutions and turned the local commons into open-access resources (Thomson *et al*., 1986; Somanathan, 1991; Baland and Platteau, 1996).

And the fourth reason is that the management of local commons often relies on social norms of behaviour, which are founded on reciprocity. But institutions that are based on reciprocity are fragile. They are especially fragile in the face of growing opportunities for private investment in substitute resources (Dasgupta, 1993, 2001a [2004]; Campbell *et al*., 2001). This is a case where an institution deteriorates even when there is no deterioration in external circumstances, nor population pressure. However, when traditional systems of management collapse and aren't replaced by institutions that can act as substitutes, the use of the local commons becomes unrestrained. The commons then deteriorate, leading to the proverbial "tragedy of the commons". In a recent study, Balasubramanian and Selvaraj (2003) have found that one of the oldest sources of irrigation - village tanks - have deteriorated over the years in a sample of villages in southern India, owing to a gradual decline in collective investment in their maintenance. The decline has come about because richer households have invested increasingly in private wells. Since poor households depend not only on tank water, but also on the fuelwood and fodder that grow round the tanks, the move to private wells on the part of the richer households has accentuated the economic stress experienced by the poor.

History tells us that the local commons can be expected to decline in importance in tandem with economic development (North and Thomas, 1973). Ensminger's (1990) study of the privatization of common grazing lands among the Orma in northeastern Kenya established that the transformation took place with the consent of the elders of the tribe. She attributed this to cheaper transportation and widening markets, making private ownership of land more profitable. The elders were, quite naturally, from the stronger families, and it did not go unnoted by Ensminger that privatization accentuated inequality within the tribe.

The point is not to lament the decline of the commons, it is to identify those who are likely to get hurt by the transformation of economic regimes. That there are winners in the process of economic development is a truism. Much the harder task is to identify the likely losers and have policies in place that act as safety nets for them.

5. Nature's Non-Convexities

Thus far, we have traced environmental problems to institutional failure and to institutional changes. We now turn to one important source of policy failure: the inappropriate modelling of ecological and economic pathways. We do that by studying non-convexities in ecological processes.

Despite the strictures of ecologists, we economists have remained ambivalent toward Nature's non-convexities. Often, that ambivalence reveals itself indirectly. For example, it is commonly thought that "... economic growth is good for the environment, because countries need to put poverty behind them in order to care", (Editorial, *The Independent*, 4 December 1999); or that "... trade improves the environment, because it raises incomes, and the richer people are, the more willing they are to devote resources to cleaning up their living space", (*The Economist*, 4 December 1999: 17).

The view's widespread acceptance in the popular press is traceable to World Bank (1992), which reported an empirical relationship between GNP per head and atmospheric concentrations of industrial pollutants. Based on the historical experience of OECD countries, the authors of the document suggested that, when GNP per head is low, concentrations of such pollutants as the sulphur oxides increase as GNP per head increases, but that when GNP per head is high, concentrations decline as GNP per head increases further. Among economists, this relationship has been christened the "environmental Kuznets curve".[22] In the popular literature, the morals that would appear to have been drawn from the finding are (1) that "the environment" is a luxury good, affordable only by the rich, and (2) that resource degradation is reversible: degrade all you want now, Earth can be relied upon to rejuvenate it later should you require it.

As general viewpoints, both presumptions are false. To be sure, there are natural amenities that could be regarded as luxuries (e.g., places of scenic beauty); however, producing as it does a multitude of ecosystem services, a large part of what Nature offers us is a necessity. We offered illustrations of this fact in the previous section when accounting for the role of the local natural resource base in the lives of the rural people in the world's poorest countries. Here, we note that Nature's non-convexities are frequently a manifestation of positive feedback processes, which in turn can mean the presence of ecological thresholds. But if a large damage were to be inflicted on an ecosystem whose ability to function is conditional on it being above some threshold level (in size, composition, or whatever), the consequence would be irreversible. The environmental Kuznets curve was detected for mobile pollutants (e.g., atmospheric pollutants). Mobility means that, so long as emissions decline, the stock at the site of the emissions declines. However, reversal is the last thing that would spring to mind should a grassland "tip" to become covered by shrubs, or should the Atlantic gulf stream shift direction or come to a halt, or should a source of water disappear, or should an ocean fishery become a dead zone owing to overfishing. As a general metaphor for the possibilities of substituting manufactured and human capital for natural capital, the relationship embodied in the environmental Kuznets curve has to be rejected.[23]

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[22] See also Cropper and Griffiths (1994) and Grossman and Krueger (1995). Copeland and Taylor (2004) is an extensive survey on the subject of trade, growth, and the environmental Kuznets curve.

[23] Arrow *et al*. (1995) contains an early interpretative commentary on the environmental Kuznets curve. Responses to that article were published in symposia in *Ecological Economics*, 1995, Vol. 15, No. 1; *Ecological Applications*, 1996, Vol. 6, No. 1; and *Environment and Development Economics*, 1996, Vol. 1, No. 1. See also the special issue of *Environment and Development Economics*, 1997, Vol. 2, No. 4.

5.1 Convex-Concave Pollution Recycling Functions

We illustrate Nature's non-convexities by studying a pollution problem that has been much analysed in recent years: phosphorus discharge into a shallow, fresh water lake (Scheffer, 1997; Carpenter *et al*., 1999; Carpenter, 2001).[24]

Phosphorus inflow into a lake is a byproduct of agriculture in the watershed. The inflow is a fertilizer runoff from farms. Phosphorus is a key determinant of the state of a lake. It is a necessary nutrient for such ecological services as those that provide a habitat for fish populations. Thus, shallow clear fresh water lakes can absorb a low level of phosphorus with little ill effect. However, if the quantity of phosphorus in the water column increases, more algae grow, meaning that less sunlight reaches the lake bottom, thus damaging the green plants on the bottom. The bottom sediments contain phosphorus in dead algae and depositions of phosphorus from the water column. The lake bottom phosphorus is harmless. However, a reduction in green plants in the lake bottom means that bottom sediments are less well protected from being flushed back into the water column by fish movements and water currents. Phosphorus is then released from the lake bottom into the water column, thereby increasing the growth of algae. This chain of events is a positive feedback. On the other hand, as noted above, some of the phosphorus in the water column continuously settles on the lake bottom, and this dampens the feedback. We now model the phenomenon.

Time is assumed to be continuous and is denoted by t (≥ 0). Let the state of a shallow fresh water lake at t be the quantity of phosphorus in the water column at that moment, which we denote by K_t (≥ 0). Let C_t (≥ 0) be the phosphorus inflow into the system at t. It has been found that the following is a good approximation of the dynamics of the state of the lake (Scheffer, 1997):

$$dK_t/dt = C_t + bK_t^2/(1+K_t^2) - ?K_t \qquad b, ? > 0. \ldots \ldots \ldots \ldots (1)$$

The positive feedback governing the recycling of phosphorus from the lake bottom into the water column is given by the second term on the right hand side of equation (1), which is convex-concave, with a least upper bound of b. The rate at which phosphorus in the water column settles on the lake bottom is given by the third term on the right hand side of equation (1). Therefore, $(bK_t^2/(1+K_t^2) - ?K_t)$ is the net natural reproduction rate of phosphorus in the water column; and ?/b is a measure of the strength of the dampeing effect that tempers the positive feedback.

For simplicity, suppose that phosphorus inflow is a constant, C. It follows that

$$dK_t/dt = C + bK_t^2/(1+K_t^2) - ?K_t \qquad K_0 \ (> 0) \text{ given.}^{25} \ldots \ldots \ldots \ldots (2)$$

[24] A mathematically identical model, concerning open access to a non-convex fishery, was presented in Dasgupta (1982).

[25] Close variants of equation (2) have been postulated for a number of natural systems. Here are three examples:

(1) In order to explain periodic infestations of the spruce budworm in boreal forests, Ludwig *et al*. (1978) postulated that the budworm's population, K_t, K_o changes in accordance with the equation

$$dK_t/dt = aKt - ßKt^2 - bKt^2/(1+Kt^2) \qquad (a, ß, b > 0). \ldots \ldots \ldots \ldots (2a)$$

where the final, forcing term denotes predation by birds.

(2) The account of the Atlantic thermohaline circulation in Rahmstorf (1995) can be formalised in terms of an equation not dissimilar to equation (2). Temperature and salt gradients across the North and South Atlantic give rise to the circulation. K_t is taken to be the North Atlantic deep water flow (travelling south) and C is the amount of fresh water entering, say, the surface of the North Atlantic (in part from ice melts). The circulation would come to a halt if C were too large.

(3) Vegetation cover in the savannahs depends on rainfall, but rainfall in turn depends on vegetation cover. Denoting rainfall by C_t and vegetation (in biomass) by K_t, suppose, as a first approximation, that

$$C_t = aK_t \text{ and } dK_t/dt = bC_t^2/(1+C_t^2) - ?Kt \qquad (a, b, ? > 0). \ldots \ldots \ldots \ldots (2b)$$

The pair of equations (2a,b) are variants of (2).

Equation (2) contains three parameters: C, b, and ?. We would like to know how the ecosystem's character depends on them. One expects that mostly the global properties of the ecosystem would vary continuously with the parameters. One should also expect that there are manifolds partitioning the parameter space into regions, such that the ecosystem's structure is the same at every point in any given region, but differs from the structure in the region adjacent to it. Such manifolds bifurcate the system's properties. To study the bifurcations, we take b and ? to be given and vary C. The reason we permit C to vary is that C denotes human intervention and we could in principle control it.

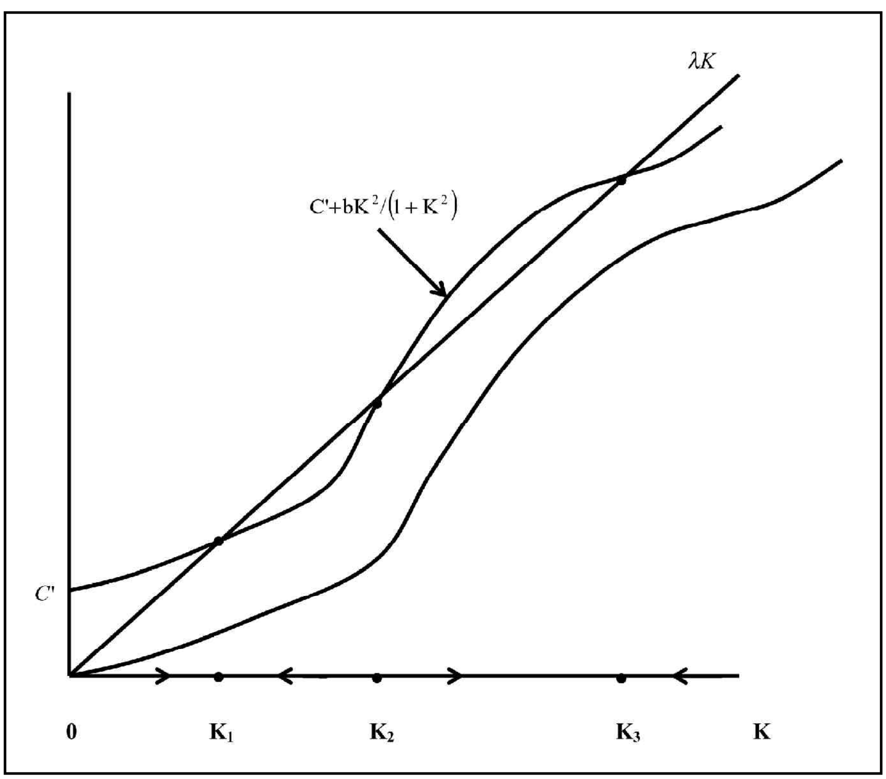
So, consider the equation

$$bK^2/(1+K^2) = ?K. \quad (3)$$

Real solutions of equation (3) are the stationary points of equation (2) with C = 0.

We begin by assuming that ?/b > 1/2, meaning that phosphorus in the water column settles in the lake bottom rapidly. In this case equation (3) has only one real solution: it is K = 0. Simple graphics (Figure 1) confirm, however, that there are values of C for which equation (2) has three (real) stationary points. Assuming one such value, $C = C'$, we label the stationary points as K_1 (<) K_2 (<) K_3, respectively. K_2 is unstable, while K_1 and K_3 are locally stable. K_2 is the separatrix of the system - the point that separates the two basins of attraction of the ecosystem. K_1 reflects an *oligotrophic* state (reasonably clear water), whereas K_3 reflects a *eutrophic* state (turbid water).

Figure 1: Dynamics of Phosphorus in Water Column
(Large dampening term)



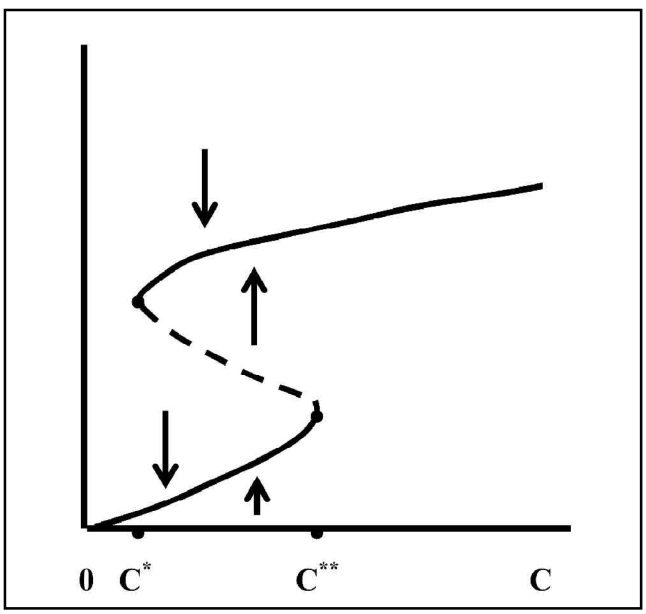
5.2 Ecosystem Flips

Continuing to hold b and ? constant, let us now reduce C from its original value C′. It is simple to confirm visually that the unstable stationary point (continue to label it K_2) and the larger of the two locally stable stationary points (continue to label it K_3) get closer to each other continuously. It is simple to confirm as well that there is a critical value of C, call it C*, for which K_2 and K_3 coincide to form a point that is stable from the right, but unstable from the left. C* is a bifurcation point of the system: if C < C*, the ecosystem possesses a unique (stable) stationary point, whereas if C > C* (but C < C**; see below), it possesses three stationary points. In short, the system's structure changes discontinuously at C*.[26]

In contrast, suppose C were to increase from C′. It is simple to confirm visually (Figure 1) that the unstable stationary point (continue to label it K_2) and the smaller of the two locally stable stationary points (continue to label it K_1) would get closer to each other continuously, until, at a critical value of C, call it C**, the two would coincide, to form a point that is unstable from the right, but stable from the left. C** is another bifurcation point of the system: if C > C**, the ecosystem possesses a unique (stable) stationary point, whereas if C < C** (but C > C*), it possesses three stationary points.

In Figure 2 we have drawn the equilibrium values of K as a correspondence of C for a given pair of values of b and ?. Equilibrium K is unique when C < C*. For C in the interval [C*, C**], the curve depicting K as a correspondence of C bends back and then back again, to reflect the fact that equation (2) possesses three stationary points. The two upward sloping portions of the correspondence consist of (locally) stable stationary values of K, whereas the downward sloping portion consists of unstable stationary points.

Figure 2: Equilibrium Correspondence of Shallow Fresh-Water Lake (The Reversible Case)



We now conduct a thought experiment. Begin in a situation where C < C*. We know that equilibrium K is small. We would like to discover how the system would change if C were to increase in a predictable way. Rather than try to integrate equation (1), we simplify by imagining that C increases slowly relative to the speed of adjustment of K_t. By "slowly" we mean that at each C the ecosystem is able to equilibrate itself. If C were to increase under such conditions, K would increase continuously along the lower arm of the curve until C = C**, at which point equilibrium K would "flip" to the upper arm of the curve. The ecosystem therefore undergoes a discrete change at C**. Further increases in C would lead to a continual increase in K along the upper arm of the curve in Figure 2.

Ecosystem flips have been observed many times and at many scales. Shallow lakes have been known to tip from clear to turbid water in a matter of months, village tanks in a matter of weeks, garden ponds in a matter of hours. Insect populations have been known to crash or explode in a matter of days. Larger ecosystems generally take

[26] Mathematicians call this a "saddle-node bifurcation".

longer to flip at their bifurcation points, because the underlying processes operate over greater distances and are therefore slower. Grasslands in sub-Saharan Africa can take more than a decade to change into shrublands. The "salt conveyor" that drives global ocean circulation would probably take between decades and a century to shut down (or change direction) if the Greenland ice cover were to melt at rates estimated in current models of global warming (Rahmstorf, 1995). The fossil records suggest that the interglacials and glacials of ice ages have appeared only occasionally, but have arrived and departed "precipitously" - the flips occuring over several thousand years. And so on.

5.3 Hysteresis in Ecosystem Dynamics

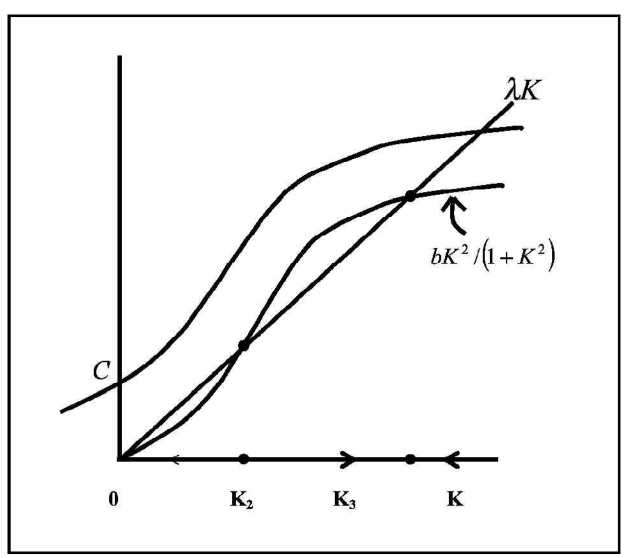
Now suppose we were to reverse the process in our previous thought experiment. Start with C > C** and reduce it slowly. Figure 2 shows that on the return journey, K declines continuously along the upper arm, so long as C > C*. This means that for C in the interval [C*, C**], K remains higher than it had been on the onward journey. To put it another way, the ecosystem displays *hysteresis*. However, at C = C* the ecosystem tips onto the lower arm of the curve in Figure 2. Further declines in K would occur continuously if C were reduced further. We conclude that even though the ecosystem displays hysteresis, environmental degradation is *reversible*: given enough time, K can be made to be as small as we like if C were reduced sufficiently. This is the intellectual basis of the environmental Kuznets curve, mentioned earlier. It would certainly be a correct view of future possibilities if the dampening term in the positive feedback were sufficiently large (?/b > 1/2).

5.4 Irreversibility

But now consider a less happy possibility. Suppose that ?/b < 1/2, which means that the positive feedback is powerful. Equation (2) possesses three real solutions. One is K = 0, while the other two are positive. Figure 3, which is the counterpart of Figure 1, depicts this case. We now use Figure 3 to construct Figure 4, which plots the equilibrium values of K as a correspondence of C. In contrast to Figure 2, the curve bends backward to cut the vertical axis.

Let us conduct the thought experiment again. Suppose we begin in a situation where both C and K are low, meaning that the system is on the lower arm of the curve in Figure 4. As C increases, K increases continuously, until the bifurcation point, C***, is reached. At this point the ecosystem flips to a higher value of K. However, once that happens, the system is incapable of reversing itself. Declines in C would certainly reduce K, but as Figure 3 shows, even if C were reduced to zero, the system would remain on the upper arm of the curve, at a higher value of K than it did to begin with. Not only does the ecosystem suffer from hysteresis, but environmental degradation is now in addition *irreversible*: the system is unable to return to where it had been in the beginning.

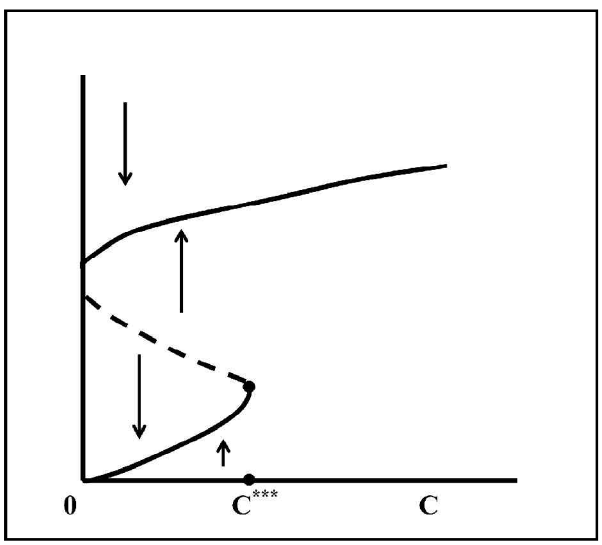
Figure 3: Dynamics of Phosphorus in Water Column (Small dampening term)



Now consider decision makers who are persuaded that the environmental Kuznets curve is a reliable summary of the complex relationships between the environment and economic development. If they were to rely on that curve to address phosphorus load in the lake, they would regard increases in phosphorus in the water column to be reversible. The irony would be that, if, in aiding economic development, the flow of phosphorus were to be allowed to go beyond C***, it would not be possible to bring the lake back to a clear state by curbing C after people become rich. Moreover, if the lake were essential to people's livelihood (and, remember, we are using "lake" as a metaphor here), the irony would be a tragedy, because the very process by which people were attempting to become rich would lead to their eventual undoing: people wouldn't *be* rich if the lake were destroyed. Even if C were reduced to zero, the lake would remain polluted. This is why the mechanism relating economic development to the environment that was invoked by *The Independent* and *The Economist*, quoted earlier, is misleading.

The "resilience" of a system is its capacity to withstand perturbations without undergoing significant changes in its character. It is neither a good nor a bad property of a system. To illustrate, suppose that the lake absorbs a constant phosphorus load C (< C**) and suppose that the lake is in an oligotrophic state (a point on the lower arm of Figure 2). Its resilience would be the extent to which it can admit an increase in phosphorus load without tipping onto a eutrophic state. A simple measure of resilience would be the distance (C**-C). Of course, the lake could be resilient in a eutrophic state too. Thus, if K represents a eutrophic state, and the lake absorbs phosphorus load C (a point on the upper arm of Figure 2), the measure of resilience would be the distance (C-C*). In the case where pollution is irreversible (Figure 4), the eutrophic state is wholly resilient: once the lake is in that state, there is no way it can be brought back to an oligotrophic state.

Figure 4: Equilibrium Correspondence of Shallow Fresh-Water Lake (The Irreversible Case)



6. Intergenerational Welfare Economics in Imperfect Economies

In Sections 3-5 we noted ways in which environmental and resource problems arise from (1) institutional failure and (2) policies emerging from the use of misspecified models of ecosystems. Within institutional failure we include failure of the State. We now use those instances to develop intergenerational welfare economics for the honest civil servant introduced in Section 1.7. We do this by determining rules that can be used to evaluate small perturbations to macroeconomic *forecasts*. Our motivation for modelling the evaluation problem in this manner is straightforward. The civil servant in question is honest and wishes to improve intergenerational welfare. But he (or she) is only a small cog in machinery of government, and so can exercise very little influence. At best, our honest civil servant has the opportunity to evaluate a perturbation to a given economic programme.

A forecast is based on a reading of technological and environmental possibilities, and on the behaviour of households, firms, communities, and the State. A perturbation to the forecast is to be interpreted as a *project* under the jurisdiction of the honest civil servant. We show below that the required evaluation rule involves the use of shadow prices that can be estimated by perturbing the forecast. The rule itself is to check whether the present discounted value of the flow of shadow profits generated by the perturbation is positive. Thus, the criterion for choice is the one that has for long been advocated for social cost-benefit analysis in optimizing economies. The analysis does not require the economy to be convex.

We also develop a criterion for assessing whether or not intergenerational welfare is sustained along an economic forecast. In the context of an economic model where population is constant, it is confirmed that the shadow prices that should be used in social cost-benefit analysis can also be used to compute an index for assessing whether intergenerational welfare is sustained. That index is a comprehensive measure of the social worth of the entire stock of the economy's capital assets, inclusive of manufactured, human, and natural capital assets. We call this *wealth*. Our analysis does not require the economy to be convex.

6.1 Resource Allocation Mechanisms

The economy to be studied is closed. Population is constant. Time is continuous and is denoted variously by t and t (t, t $\geq$ 0). The horizon is taken to be infinite. For simplicity of exposition, we aggregate consumption into a single commodity flow, C, and let **R** denote a vector of resource flows (e.g., rates of extraction of natural resources, expenditure on education and health).

We are thinking of an economy here in a broad sense. Depending on the context in which a study is conducted, the economy could be a household, a village, a district, a province, a nation, or, at the grandest level of aggregation, the world as a whole. The state of the economy is represented by the vector **K**, where **K** is a comprehensive list of capital assets, including not only manufactured capital, knowledge and skills, but also natural capital. For notational simplicity, we eschew intratemporal allocation problems here. Were they to be included, **K** would be a vector of a larger dimension. Capital assets would be "named" in terms of the character of their ownership, in the way general equilibrium theory has made familiar.

Certain types of natural capital are directly valuable as stocks in production and consumption (e.g., resources having intrinsic value). For expositional ease, we assume in this section that such stock effects are absent. Labour is assumed throughout to be supplied inelastically and is normalised to be unity. Current utility is therefore taken to depend only on consumption. We write this as U(C), where U(C) is a strictly concave, twice differentiable, and monotonically increasing function.[27] Intergenerational welfare - henceforth, *social welfare* - at t ($\geq$ 0) is

$$W_t = \int_t^{\infty} U(C_t)e^{-d(t-t)}dt \quad d > 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

(Koopmans, 1972, uncovered ethical axioms that yield expression (4) as the index of social welfare.)

We now formalise the idea of an *imperfect economy* (Dasgupta and Mäler, 2000; Dasgupta, 2001a [2004]; Arrow *et al*., 2003a). Assume that the economy faces not only technological and ecological constraints, but also a wide variety of institutional constraints (sometimes called transaction and information constraints). By the economy's institutions we mean market structures, the structure of property rights, tax rates, non-market institutions (for credit, insurance, and common property resources), the character of various levels of government, and so forth. We do not assume that the government is bent on maximizing social welfare subject to constraints. As noted earlier, it could be that the government is predatory, or is at best neglectful, and has objectives of its own that are not congruent with citizens' welfare. Nor is it assumed that institutions are unchanging. What we do assume is that institutions co-evolve with the state of the economy (**K**) in ways that are understood. It is no doubt a truism that social and political institutions influence the evolution of the state of an economy, but it has also been argued by political scientists (Lipset, 1959) that the state of an economy (**K**) influences the evolution of social and political institutions. The theory presented here accommodates this mutual influence.

Let $\{\mathbf{C}_t, \mathbf{R}_t, \mathbf{K}_t\}_t \infty$ be an *economic programme* from t to ∞. Given technological possibilities, resource availabilities, and the dynamics of the ecological-economic system, the decisions made by individual agents and consecutive governments from t onwards will determine C_t, $\mathbf{R}_t$, and $\mathbf{K}_t$ - for $t \geq t$ - as functions of K_t, t, and t. Thus if K_t is the vector of capital assets at t, let $f(\mathbf{K}_t, t, t)$, $g(K_t, t, t)$, and $\mathbf{h}(\mathbf{K}_t, t, t)$, respectively, be consumption, the vector of resource flows, and the vector of capital assets at date t $(\geq t)$. $\{C_t, R_t, K_t\}_t^{\infty}$ can therefore also be thought of as an *economic forecast* at t. Now write

$$(\mathbf{?}_t)_t^{\infty} \equiv \{\mathbf{C}_t, \mathbf{R}_t, \mathbf{K}_t\}_t^{\infty} \quad t \geq 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

Let $\{t, \mathbf{K}_t)\}$ denote the set of possible t and $\mathbf{K}_t$ pairs, and $\{(\mathbf{?}_t)_t\infty\}$ the set of economic programmes from t to infinity.

Definition 1. A *resource allocation mechanism*, a, is a (many-one) mapping

$$a: \{t, K_t\} \rightarrow \{(?_t)_t^{\infty}\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

We do *not* assume that a maps $\{t, \mathbf{K}_t\}$ into optimum economic programmes (starting at t), nor even that it maps $\{t, \mathbf{K}_t\}$ into efficient programmes (starting at t). The following analysis is valid even if a is riddled with economic distortions and inequities. As noted above, nor do we assume that the economy's institutions are fixed. If institutions and the state of the economy were known to co-evolve, that co-evolution would be reflected in a. Note too that we do *not* assume transformation possibilities among commodities and services to constitute convex sets.

Institutional assumptions underlie the notion of resource allocation mechanism. For example, aspects of the concept of "social capital" (Putnam, 1993), ideas relating to "social capability" (Adelman and Morris, 1965; Abramovitz, 1986), and the notion underlying the term "social infrastructure" (Hall and Jones, 1999) appear as part of the defining characteristics of a. Moreover, the prevalence (or absence) of trust and honest behaviour in the economy are embodied in a, as are mutual expectations of one another's intentions. However, one important aspect of the

[27] The following analysis does not require U to be concave. We assume concavity none the less for ethical reasons: (strict) concavity reflects concern for equity, both among people of the same generation and among people of different generations.

concept of social capital, namely, interpersonal networks, is a component of human capital, and therefore appears in the vector **K**. (Dasgupta, 2003b, elaborates on the classification.)

To make the dependence of the economic forecast on a explicit, let $\{C_t(a), \mathbf{R}_t(a), \mathbf{K}_t(a)\}_0^\infty$ denote the forecast at t = 0. Consider date t (≥ 0). We may now write equation (4) as,

$$W_t \equiv \int_t^\infty U(C_t(a))e^{-d(t-t)}dt \qquad (7)$$

which is social welfare at t. W_t is a function of the state of the economy, $\mathbf{K}_t$, and the resource allocation mechanism, a. So we can express it as the *value function*:

$$V(\mathbf{K}_t, a, t) \equiv W_t \equiv \int_t^\infty U(C_t(a))e^{-d(t-t)}dt \qquad (8)$$

It transpires that the value function is a more useable object in the welfare economics of imperfect economies than the familiar Hamiltonian of dynamic optimization theory. So we work with the value function here.

Before putting the concept of resource allocation mechanism to work, it is as well to discuss examples. (In Sections 7-8 we illustrate by means of formal models.)

1. Consider a one-commodity world with constant population. Households save a constant proportion, s (0 < s < 1), of output. Capital depreciates at a constant rate ? (> 0). Assume that if K is the stock of the capital asset, F(K) is aggregate output, where F′(K) > 0, sF′(0) > ?, and F″(K) < 0. It follows that capital accumulates according to the dynamics

   $$dK_t/dt = sF(K_t) - ?K_t, t \geq t \geq 0$$

   (The above is a stripped-down version of the Solow model of economic growth). An economic programme at t can be expressed as $\{C_t, K_t\}_t^\infty$, where $C_t = (1\text{-}s)F(K_t)$. The above specification defines a resource allocation mechanism.

2. Imagine a first-best economy. There the resource allocation mechanism a maps ($\mathbf{K}_t$,a,t) to the corresponding optimum programme. Much of the literature on the welfare economics of the environment has been based on this mechanism. (Heal, 1998, contains a fine exposition of first-best allocations.)

3. Assume that all capital assets are private property and that there is a complete set of competitive forward markets capable of sustaining a unique equilibrium. In this case a maps ($\mathbf{K}_t$,a,t) to the equilibrium. (If equilibrium is not unique, a selection rule among the multiple equilibria would have to be specified.) Much modern macroeconomics is founded on this mechanism.

4. Of particular interest are situations where some of the assets are not private property. Consider the cases where manufactured capital is private property, but natural capital is common property (Section 4). It may be that natural capital assets are local common property resources, not open to outsiders. If assets are managed efficiently, we are in effect back to the case of a competitive equilibrium allocation, albeit one not entirely supported by market prices, but in part by, say, social norms.

5. On the other hand, it may be that local institutions are not functioning well (e.g., because social norms are breaking down and private benefits from using environmental natural resources exceed social benefits).

Suppose in addition that decisions bearing on the accumulation of manufactured capital are guided by the profit motive. Then these behavioural rules together help to determine a. In a similar manner, we could (as we do in Section 7) characterize a for the case where there is open access to a natural resource base.

Definition 2. a is *time autonomous* (henceforth *autonomous*) if for all $t \geq t$, **?**(t) is a function solely of $\mathbf{K}_t$ and $(t\text{-}t)$.

If a is autonomous, economic variables at date t $(\geq t)$ are functions of $\mathbf{K}_t$ and $(t\text{-}t)$ only. So a would be non-autonomous if, say, knowledge, or the terms of trade (for a trading economy), were to change exogenously over time. In Section 6.5 we have occasion to comment further on the reasonableness of regarding a as autonomous.

Definition 3. a is time-consistent if

$$\mathbf{h}(\mathbf{K}_t{}',t'',t') = \mathbf{h}(\mathbf{K}_t,t'',t), \text{ for all } t'', t', \text{ and } t.. \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Time-consistency implies a weak form of rationality. An autonomous resource allocation mechanism, however, has little to do with rationality; it has to do with the influence of external factors (e.g., whether trade prices are changing autonomously). In what follows, it is assumed that a is time-consistent.

6.2 Differentiability of the Value Function

Let K_i be the ith capital stock. We assume that V is right- and left-differentiable in K_i for all i everywhere. Unaided intuition could suggest that this is a strong assumption. The mathematical properties of V depend upon the mathematical properties of a, and problems are compounded because production and substitution possibilities in the economy are embodied in a, as is the economy's underlying institutional structure. Moreover, there are no obvious limits to the kinds of institutions one can imagine. In many parts of the world the State has been known to act in bizarre and horrible ways. Nevertheless, we argue below that the assumption is weak. In any case, if the location of the points at which V is non-differentiable is uncertain and the uncertainty is a sufficiently smooth probability distribution, the *expected value* of V would be differentiable everywhere.

6.3 Shadow Prices

We confirm below that shadow prices are useful in imperfect economies, whether or not they are convex. First, we define them. It would simplify the exposition if we could avoid mentioning left- and right-derivatives of V. So, in what follows, we work on the assumption that V is differentiable.

Definition 4. The shadow price, p_{it}, of the ith capital asset is defined as

$$p_{it} = \partial V_t/\partial K_{it} \equiv \partial V(\mathbf{K}_t,a,t)/\partial K_{it}. \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

In expression (10), p_{it} is the spot price of K_{it}; it is the asset's social scarcity value. Note that shadow prices are defined in terms of hypothetical perturbations to an economic forecast. The shadow price of a capital asset is the present discounted value of the perturbations to U that would arise from a marginal increase in the asset's quantity. Notice also that the shadow price of a private commodity could be negative in an imperfect economy even if it would have been positive if the economy were a well-managed one. For example, consider that when a fossil fuel is burnt, the resulting pollutant is emited into the atmosphere. If the atmosphere as a sink is a free good, the result is a tragedy of the commons. The shadow price of the fossil fuel would be negative if the social damage that is caused when someone burns the fuel exceeds the private benefit to that person. In a well-managed economy, the negative externality would not exist.

Given the resource allocation mechanism a, shadow prices at t are functions of $\mathbf{K}_t$ and, if a is non-autonomous, of t as well. Thus, $p_{it} = p_{it}(\mathbf{K}_t)$. The prices depend also on the extent to which various capital assets are substitutable for one another. If a is autonomous, shadow prices do not depend explicitly on time, and so, $p_{it} = p_i(\mathbf{K}_t)$. All future effects on the economy of changes in the structure of assets are reflected in shadow prices. That is why they are useful objects. Having stressed their functional dependence on a and **K** (and, possibly, t as well), we drop a and **K** from the formulae so as to save on notation.

6.4 Marginal Rates of Substitution vs Market Observables

Using equations (8) and (10), one can show that if a is autonomous, p_{it} satisfies the equation,

$$dp_{it}/dt = dp_{it} - U'(C_t)\partial C_t/\partial K_{it} - S_j p_{jt}\partial(dK_{jt}/dt)/\partial K_i. \qquad (11)$$

Equation (11) reduces to the Pontryagin equations for co-state variables in the case where a is an optimum resource allocation mechanism.[28] However, in order to study the evolution of shadow prices under simple resource allocation mechanisms, it is more intuitive to work directly with (10); which is why the familiar Hamiltonian of dynamical systems does not make an appearance in our account.

From equation (10) it also follows that shadow price ratios (p_{it}/p_{jt}, p_{it}'/p_{it}), and consumption discount rates (see below) are defined as marginal social rates of substitution between goods. In an economy where the government maximizes social welfare, marginal rates of substitution among goods and services equal their corresponding marginal rates of transformation. As the latter are observable in market economies (e.g., border prices for traded goods in an open economy), shadow prices are frequently defined in terms of marginal rates of transformation among goods and services. However, marginal rates of substitution in imperfect economies do not necessarily equal the corresponding marginal rates of transformation. This is why shadow prices are difficult to estimate in imperfect economies. A distinction needs to be made between the ingredients of social welfare and market observables. Using market observables to infer social welfare can be misleading in imperfect economies. That we may have to be explicit about ethical parameters (e.g., d and the elasticity of U) in order to estimate marginal rates of substitution in imperfect economies is not an argument for pretending that the economies in question are not imperfect after all. In principle it could be hugely misleading to use the theory of optimum control to justify an exclusive interest in market observables.

6.5 Wealth, (Inclusive) Investment, and Sustainable Welfare

The phrase “sustainable development” was introduced by the International Union for the Conservation of Nature and Natural Resources (IUCN, 1980). The publication drew attention to the role played by the natural environment in our economic life. But the phrase become a commonplace only after the publication of a report by the World

[28] In Dasgupta and Mäler (2000) it was mistakenly claimed that it does so even in imperfect economies. We are grateful to Geir Asheim for correcting the error in that article and deriving equation (11).

Commission on Environment and Development (WCED), widely known as the Brundtland Commission Report, where sustainable development was defined as "... development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987: 43). The idea is that, relative to their respective demographic bases, each generation should bequeath to its successor at least as large a productive base as it had inherited from its predecessor. If it were to do so, the economic possibilities facing the successor would be no worse than those it faced when inheriting productive assets from its predecessor.

The notion of sustainable development therefore invites us to seek a measure that would enable us to judge whether an economy's productive base is growing. Consider, however, an interpretation of sustainability that is based on the maintainence of social welfare, rather than on the maintainance of the productive base:

Definition 5. The economic programme $\{C_t, \mathbf{R}_t, \mathbf{K}_t)\}_0\infty$ corresponds to a sustainable development path *at t* if $dV_t/dt \geq 0$.

Below we show that the requirement that economic development be sustainable implies, and is implied by, the requirement that the economy's productive base be maintained (Propositions 1-3). These results give intellectual support for Definition 5, which is why we do not go into various alternative definitions of sustainable development here.[29]

Notice that the criterion for sustainablity in Definition 5 does not identify a unique economic programme. In principle any number of technologically and ecologically feasible economic programmes could satisfy the criterion. On the other hand, if substitution possibilities among capital assets are severely limited and technological advances are unlikely to occur, it could be that there is no sustainable economic programme open to an economy. Furthermore, even if the government were bent on maximizing social welfare, the chosen programme would not correspond to a sustainable path if the welfare discount rate, d, were too high (Dasgupta and Heal, 1974). It could also be that along an optimum path social welfare declines for a period and then increases thereafter, in which case the optimum programme does not correspond to a sustainable path locally, but does so in the long run.[30]

Optimality and sustainability are thus different notions. The concept of sustainability helps us to better understand the character of economic programmes, and is particularly useful for judging the performance of imperfect economies.

Definition 6. *Inclusive investment* at t, I_t, is $I_t = S_i(p_{it}dK_{it}/dt)$.[31]

Differentiating equation (8) with respect to t, we have

Proposition 1. $dV_t/dt = \partial V_t/\partial t + S_i p_{it} dK_{it}/dt$. . . . . (12)

[29] Pezzey (1992) and Pezzey and Toman (2002) are penetrating accounts of various interpretations of the idea of sustainable development.

[30] Kenneth Arrow has produced an example of an optimum economic programme displaying such a feature.

[31] Dasgupta (2001a, [2004]) and Arrow *et. al* (2004) call this *genuine investment*.

If a is autonomous, $\partial V_t/\partial t = 0$, and we have

Proposition 2. $dV_t/dt = S_i p_{it} dK_{it}/dt = I_t$. . . . . (13)

Equation (13) states that if a is autonomous, inclusive investment equals the rate at which social welfare changes.[32]

Definition 7. Inclusive wealth at t is $S_i p_{it} K_{it}$.

Notice that inclusive investment is the rate at which inclusive wealth changes, while holding shadow prices constant. Therefore, Proposition 2 states that if a is autonomous, the rate at which social welfare changes equals the rate at which inclusive wealth changes, while holding shadow prices constant.

There is a sense in which, the smaller is the unit that is being called an “economy”, the less likely it is that a would be autonomous. A household, for example, faces terms of trade with the rest of the world, over which it has no control. If those terms are expected to change over time, the resource allocation mechanism within the household would not be autonomous. In contrast, changes in the terms of trade would be endogenous in any detailed analysis of the world economy. In other words, if the terms of trade were expected to change, a convincing exercise in political economy would found those changes on the state of the economy, or in other words, on **K**. And this would mean that a would be autonomous in so far as it pertains to the terms of trade.

Similar remarks apply to technological change. Improvements in available knowledge are mostly exogenous to the household. The household can, of course, ride on those changes only if it acquires the necessary human capital (a component of household capital), but improvements in available knowledge would not depend on the household’s capital base; rather, the household would shape its portfolio of capital assets in response to the available knowledge and to the anticipated changes in available knowledge. In contrast, improvements in the knowledge base for the world economy as a whole should be attributable to research and development. Serendipidy no doubt plays a role, but it has been suggested by scientists that in research, luck visits only the prepared mind. Recall that in growth accounting, the “residual” is the amount of growth in output that cannot be attributed to changes in those production inputs that the investigator has been able to measure. There is no suggestion in the growth literature that if capital assets were comprehensively accounted for, there would be any residual left. Certainly, the development of endogenous growth theories was motivated by this viewpoint. In a fully articulated endogenous growth model, a would be autonomous.

Proposition 2 is a local measure of sustainability. Integrating (13) yields a non-local measure:

Proposition 3. If a is autonomous, then for all $T \geq 0$,

$$V_T - V_0 = S_i(p_{iT}K_{iT} - p_{i0}K_{i0}) - {}_0\!\int^T [S_i(dp_{it}/dt)K_{it}]dt \quad . . . . \quad (14)$$

Equation (14) shows that in assessing whether or not social welfare has increased between two dates, the capital gains on the assets that have accrued over the interval should be deducted from the difference in inclusive wealth between the dates.

[32] This result was proved (and its significance recognised) for optimally managed, convex economies by Pearce and Atkinson (1995). Significant precursors to their result were Samuelson (1961), Solow (1974), and Hartwick (1977). Dasgupta and Mäler (2000) proved the result for arbitrary economies. Arrow *et al*. (2003a) contains the most general results to date on the equivalence between sustainable development and wealth movements. (They studied arbitrary economies, where population is not constant and where exogeneous technological and institutional changes occur.)

Each of Propositions 1, 2 and 3 is an equivalence result. None of the propositions says whether a gives rise to an economic programme along which social welfare is sustained. For example, it can be that an economy is incapable of achieving a sustainable development path, owing to scarcity of resources, limited substitution possibilities among capital assets, or whatever. Or it can be that although the economy is in principle capable of achieving a sustainable development path, welfare is unsustainable along the path that has been forecast because of bad government policies. Or it can be that a is optimal, but that because the welfare discount rate d has been chosen to be large, social welfare is not sustained along the optimum economic programme. Or it can be that along an optimum path social welfare declines for a period and then increases thereafter.

Imagine that substitution possibilities are limited, and the resource allocation mechanism in place is profligate in the use of natural resources. Under these circumstances the quality of life will not be sustainable. At some date in the future shadow prices will assume such values as to make it impossible for inclusive wealth to be maintained. As Proposition 2 shows, social welfare declines if inclusive investment is negative.

6.6 GNP and NNP vs Wealth

GNP is a short term measure of welfare because it does not recognise capital depreciation. In contrast, inclusive investment is investment *net* of capital depreciation. We next show that it is possible for GNP to increase over a period of time even while wealth declines.

Consider the stylised model of a "cake eating" economy, by which we mean an economy where the rate of return on investment is zero. Imagine that the economic programme that is forecast involves continual increase in consumption during a finite period [0, T], to be followed by a steady decline to zero. Assume that it is expected that the entire cake will be consumed over the infinite horizon. If K_0 is the initial stock of "cake", it would follow that

$$\int_0^T C_t dt + \int_T^\infty C_t dt = K_0,$$

where $dC_t/dt > 0$ for $t \in [0, T]$ and $dC_t/dt < 0$ for $t \in [T, \infty)$.

Notice that GNP (equal to consumption) increases at every moment during [0, T], but declines subsequently. However, wealth (at constant utility price; Proposition 1) is a declining function at each moment. We therefore have

Proposition 4. GNP could increase for an interval of time even while wealth declines.

Propositions 1-4 provide the basis on which the conflicting intuitions sketched in Section 1.2 have been held by their respective protagonists.

What of *net* national product (NNP) as a measure of social welfare? Dasgupta and Heal (1979: Ch. 8) noted that in the cake eating economy NNP is zero all along an *optimum* consumption programme, because (i) consumption at each moment equals cake depletion and (ii) the utility price of consumption equals the utility price of the cake. Since wealth declines along the optimum, there is a dissonance between the directions of movements in NNP and wealth. In imperfect economies, the dissonance can be even greater.

To confirm, suppose that

$$U(C) = -C^{-?} \qquad ? > 1 \ldots\ldots (15)$$

Consider the programme $\{C_t\}_0^{\infty}$, where

$$C_t = ?K_0e^{-?t} \qquad ? > 0 \ldots\ldots (16)$$

(It is well known that $\{C_t\}_0^{\infty}$ is optimal if ? = d/?.) The resource allocation mechanism implied by equation (16) is autonomous. Using equation (16) in equation (15), we have

$$U'(C_t) = ?(?K_t)^{-(?+1)} \ldots\ldots (17)$$

Expression (17) gives us the shadow price of consumption in utility numeraire.

Assume that d > ??. To compute the shadow price of the cake, use equations (8) and (15)-(16) to obtain,

$$V(K_t) = -(?K_t)^{-?}\int_t^{\infty}[e^{-(d-??)(t-t)}]dt$$

$$= -(?K_t)^{-?}/(d-??),$$

from which we have

$$p_t = V'(K_t) = ??^{-?}(K_t)^{-(?+1)}/(d-??) \ldots\ldots (18)$$

But NNP at t is,

$$(NNP)_t = (U'(C_t) - p_t)C_t. \ldots\ldots (19)$$ [33]

Consider the case ?? < d < (1+?)?. Then from equations (17) and (18), $U'(C_t) < p_t$, implying that $(NNP)_t < 0$. From equation (16), $dC_t/dt < 0$. Thus, at constant shadow prices, NNP increases at each t. But we know that, at constant prices, wealth declines along the consumption programme (16). This proves that NNP and wealth, at constant prices, can move in opposite directions.

6.7 What Else Does Inclusive Investment Measure?

Imagine that the capital base at t is not $\mathbf{K}_t$, but $\mathbf{K}_t$+? $\mathbf{K}_t$, where ? is an operator signifying a small difference. In the obvious notation,

$$V(a, \mathbf{K}_t+?\mathbf{K}_t) - V(a, \mathbf{K}_t) \approx \int_t^{\infty}U'(C_t)?C_te^{-d(t-t)}dt \ldots\ldots (20)$$

Now suppose that at t there is a small change in a, but only for a brief moment, ? t, after which the resource allocation mechanism reverts back to a. We write the increment in the capital base at t+? t consequent upon the

[33] If ? = d/?, then from equations (16) and (17) it follows that (NNP)t = 0 at all t.

brief increase in inclusive investment as ? $\mathbf{K}_t$. So ? $\mathbf{K}_t$ is the consequence of an increase in inclusive investment at t and ($\mathbf{K}_{t+?t}$ + ? $\mathbf{K}_t$) is the resulting capital base at t+? t. Let ? t tend to zero. From equation (20) we obtain

Proposition 5. Inclusive investment measures the present discounted value of the changes to consumption brought about by it.[34]

6.8 Policy Evaluation

Proposition 5 gives us the tools required to develop a theory of policy evaluation in imperfect economies. Imagine that even although the government does not optimize, it can bring about small changes to the economy by altering the existing resource allocation mechanism in minor ways. The perturbation in question could be small adjustments to the prevailing structure of taxes for a short while, or it could be minor alterations to the existing set of property rights for a brief period, or it could be a small public investment project. We call any such perturbation a *policy reform*.

Consider as an example an investment project. It can be viewed as a perturbation to the resource allocation mechanism a for a brief period (the lifetime of the project), after which the mechanism reverts back to its earlier form. We consider projects that are small relative to the size of the economy. How should they be evaluated?

For simplicity of exposition, we suppose there is a single output, Y (which serves also as the consumption good), a single manufactured capital good (K), and a single extractive natural resource (S). The rate of extraction is denoted by R. Let the project's lifetime be the period [0, T]. Denote the project's output and inputs at t by the vector (? Y_t, ? L_t, ? K_t, ? R_t).[35]

The project's acceptance would perturb consumption under a. Let the perturbation at t (≥ 0) be $\underline{?}\,C_t$. It would affect U_t by the amount $U'(C_t)\underline{?}\,C_t$. However, because the perturbation includes all "general equilibrium effects", it would be tiresome if the project evaluator were required to estimate $\underline{?}\,C_t$ for every project that came up for consideration. Shadow prices are useful because they enable the evaluator to estimate $\underline{?}\,C_t$ indirectly. Now, it is most unlikely that consumption and investment have the same shadow price in an imperfect economy. So we divide ? Y_t into two parts: changes in consumption and in investment in manufactured capital. Denote them as ? C_t and ? (dK_t/dt), respectively.

U is the unit of account.[36] Let w_t denote the accounting wage rate. Next, let p_t be the accounting price of manufactured capital, q_t the accounting price of the extractive resource input of the project, and $?_t$ the social cost

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[34] Proposition 5 is familiar for economies where the government maximises intergenerational welfare (see Arrow and Kurz, 1970).

[35] Proposition 5 is familiar for economies where the government maximises intergenerational welfare (see Arrow and Kurz, 1970).35 If the project has been designed efficiently, we would have:

$$?Y_t = (\partial F/\partial K)?K_t + (\partial F/\partial L)?L_t + (\partial F/\partial R)?R_t,$$

where F is an aggregate production function (Y = F(K,L,R)). The analysis that follows in the text does not require the project to have been designed efficiently. As we are imagining that aggregate labour supply is fixed, $?L_t$ used in the project would be the same amount of labour displaced from elsewhere.

[36] Dasgupta *et al*. (1972) and Little and Mirrlees (1974), respectively, developed their accounts of social cost-benefit analysis with consumption and government income as numeraire. Which numeraire one chooses is, ultimately, not a matter of principle, but one of practical convenience.

of borrowing capital (i.e. $?_t = d - (dp_t/dt)/p_t$).[37]
From the definition of accounting prices, it follows that

$$ {}_0\!\int^{\infty} U'(C_t)\underline{?}\,C_t e^{-dt}dt \;=\; {}_0\!\int^{T}(U'(C_t)?\,C_t + p_t?\,(dK_t/dt) - w_t?\,L_t - ?_t p_t?\,K_t - q_t?\,R_t)e^{-dt}dt \;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\; (21) $$

But the right hand side of equation (21) is the present discounted value of social profits from the project, in utility numeraire. Moreover, ${}_0\!\int^{\infty} U'(C_t)\underline{?}\,C_t e^{-dt}dt = ?\,V_0$, the latter being the change in social well-being that would be experienced if the project were accepted. We may therefore write equation (21) as,

$$?\,V_0 \;=\; {}_0\!\int^{T}(U'(C_t)?\,C_t + p_t?\,(dK_t/dt) - w_t?\,L_t - ?_t p_t?\,K_t - q_t?\,R_t)e^{-dt}dt \;.\; (22) $$

Equation (22) leads to the well-known criterion for project evaluation:

Proposition 6. A project should be accepted if and only if the present discounted value of its social profits is positive.

Notice the connection between equations (13) and (22): they say the same thing. Proposition 6 brings out the connection between wealth as a measure of social welfare (Proposition 2) and the present discounted value of changes in consumption occasioned by a marginal change in inclusive investment (Proposition 5). Proposition 6 says that the way to evaluate an investment project is to compare reductions in short-term welfare resulting from the project's investment outlay to the increase in wealth those reductions help to create.

7. Estimating Shadow Prices: Two Examples

Estimating shadow prices requires empirical ingenuity. A prior problem is to derive expressions for shadow prices that are based on the character of the resource allocation mechanism a and on welfare parameters. In this section we conduct two exercises to illustrate how shadow prices could be derived. One involves valuing an open access aquifer, while the other illustrates how shadow prices can be estimated even when the underlying process is non-convex. We could derive both shadow prices by integrating equation (11) - the Pontryagin equation. We follow the more intuitive route by working directly with equation (10) instead.

7.1 Open Access Pool

Shadow prices of exhaustible resources in an economy where depletion rates are optimal have been much studied. What is the structure of their shadow prices when resources are instead common pools?

It is simplest if we avoid a complete capital model. So we resort to a partial equilibrium world: income effects are assumed to be negligible. Consider then an aquifer that is subject to open access. Let R_t be the quantity of water

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[37] Thus

$q_t = {}_t\!\int^{\infty} U'(C_t)\partial C_t/\partial R_t e^{-d(t-t)}d_t$

Notice that if manufactured capital were to depreciate at a constant rate, say ?, the social cost of borrowing capital would be $?_t = d + ? - (dp_t/d_t)/p_t$.

Let $\underline{q}_t$ be the accounting price of the resource *in situ*. At a full-optimum, $p_t\partial F/\partial R_t = q_t = \underline{q}_t$, and $U'(C_t) = p_t$

extracted at t. Income is the numeraire. Let U(R) be the area under the demand curve below R. So U′(R) is the market demand function. U is assumed to be an increasing and strictly concave function of R for positive values of R. As before, the discount rate is a constant, d. Let K_t be the stock in the aquifer at t. Then,

$$dK_t/dt = -R_t. \qquad (23)$$

Let the unit extraction cost of water be a constant m (> 0). Under open access, Hotelling rents are dissipated completely. Therefore, the equilibrium extraction rate, R_t, is the solution of the equation,

$$U'(R_t) = m. \qquad (24)$$

Equation (24) confirms that, irrespective of the size of the pool, there is excessive extraction. Let R* be the solution of equation (24). We then have,

$$dK_t/dt = -R^*.$$

Reserves remain positive for a period $T = K_0/R^*$. Let us normalize utility by setting U(0) = 0. It follows that,

$$V_t = \int_t^{(t+K(t)/R^*)}[U(R^*) - mR^*]e^{-d(t-t)}dt \qquad (25)$$

Let p_t be the shadow price of a unit of water in the aquifer. Then,

$$p_t = dV_t/dK_t = [(U(R^*) - mR^*)/R^*]\exp(-dK_t/R^*) > 0. \qquad (26)$$

Write $p_t^* = p_t/U'(R^*)$, which is the ratio of the shadow price to unit extraction cost. From equations (25)-(26),

$$p_t^* = [(U(R^*) - mR^*)/mR^*]\exp(-dK_t/R^*) > 0. \qquad (27)$$

Equation (27) resembles a formula proposed by El Serafy (1989) for estimating depletion charges.[38] The charge is positive because an extra unit of water in the aquifer would extend the period of extraction. Notice that p_t^* is bounded above by the ratio of the Marshallian consumer surplus to total extraction cost. Moreover, it increases as the aquifer is depleted and attains its upper bound at the date at which the pool is exhausted. If reserves are large, p_t^* is small, and open access involves no great loss - a familiar result.

What are plausible orders of magnitude? Consider the linear demand function. Assume therefore that

$$U(R) = aR - bR^2, \qquad a > m \text{ and } b > 0. \qquad (28)$$

From equations (24) and (28),

$$R^* = (a - m)/2b. \qquad (29)$$

[38] See also Hartwick and Hageman (1993) for a fine discussion that links El Serafy's formula to Hicks' formulation of the concept of national income (Hicks, 1942).

Substituting equations (28) and (29) in equation (27),

$$p_t^* = [(a-m)/2m]\exp[(-2bdK_t)/(a-m)]. \ldots\ldots (30)$$

Equation (30) says that

$$p_t^* \geq 1 \text{ iff } dS \leq [(a-m)/2b]\ln[(a-m)/2m].$$

Equation (30) expresses p* in terms of the parameters of the model. Suppose, for example, that d = 0.02 per year, K/R* = 100 years (i.e., at the current rate of extraction, the aquifer will be exhausted in 100 years), (a-m)/2m = 20 (e.g., m = \$0.50 and (a-m) = \$20). Then $p^* = 20e^{-2} \approx 7$. We should conclude that the value to be attributed to water at the margin is high (7 times extraction cost). As the date of exhaustion gets nearer, the shadow price rises to its upper bound, 20.

7.2 Shadow Price of Phosphorus in a Shallow Lake

Brock and Starrett (2003) have analysed the optimum discharge of phosphorus into the shallow, fresh water lake we studied in Section 5. Since phosphorus runoff into the lake is a byproduct of agriculture, the runoff itself is a benefit to society. In the water column of the lake, phosphorus as a stock is beneficial when the level is low (it is a nutrient for fish), but is deletarious when the level is not low. However, for simplicity, Brock and Starrett assumed that, as a stock in the water column, phosphorus is "bad", regardless of its level. As before, let C_t be the runoff into the lake and K_t the stock in the water column. Brock and Starrett (2003) assumed the utility function to be of the form,

$$U(C_t, K_t) = \log C_t - hK_t^2 \qquad h > 0.\text{[39]} \ldots\ldots (31)$$

Here, we are interested in an imperfect economy. There are many farmers in the catchments area of the lake, and they all freely discharge phosphorus into the lake. Shadow prices are useful objects in such a world.

Consider a stationary economy, where the total runoff is a constant, C. Recall that the dynamics of phosphorus stock in the water column is given by the equation

$$dK_t/dt = C + bK_t^2/(1+K_t^2) - ?K_t, ? \qquad b > 0 \text{ and } K_0 \ (> 0) \text{ given}. \ldots (32)$$

Imagine that the lake has equilibrated, so that the level of phosphorus in the water column is given by a solution (see Figures 2 and 4) of

$$C + bK^2/(1+K^2) - ?K = 0. \ldots\ldots (33)$$

[39] The authors showed that, typically, there are multiple stationary points of the differential equations that the optimum runoff necessarily satisfies; and that the stationary runoff rate which ought to be society's long run aim depends on the initial level of phosphorus in the water column. (See also Keeler *et al*., 1972.) More interestingly, they showed that the familiar "transversality condition" in optimum control theory, used in convex optimization problems in conjunction with the conditions necessary for optimality, is *not* sufficient: given the initial level of phosphorus in the water column, the planner would have to compute social welfare along each of the policies that satisfy the necessary conditions for optimality and tend in the long run to a stationary runoff rate and compare them. In other words, a non-convex optimization problem, such as this, cannot be decentralised by means of a system of shadow prices: the planner has to conduct global cost-benefit analysis. For a pioneering analysis of optimizing a non-convex dynamical system, see Skiba (1978).

For concreteness, we consider the case ?/b > 1/2. The relevant diagram is Figure 2. Assume $C \neq C^*$ and $C \neq C^{**}$. Let $\underline{K}$ be that stable solution of equation (33) at which the system has equilibrated. Along this programme, social welfare (equation (8)) is

$$V(\underline{K}) = (\log C - h\underline{K}^2)/d. \qquad (34)$$

Let $p(\underline{K})$ be the shadow price of phosphorus in the water column. In order to estimate it, imagine that at $t = 0$, $\underline{K}$ is increased by e_0. Since the phosphorus load remains fixed at C (farmers don't care what the state of the lake is; they only care about farming), the lake returns to $\underline{K}$. Let $K_t = (\underline{K} + e_t)$. Linearising the expression on the left hand side of equation (33) round $\underline{K}$ (which is a stable equilibrium), it is simple to confirm that

$$e_t = e_0 e^{-?t} \qquad ? = ? - 2b\underline{K}/(1+\underline{K}^2)^2 > 0. \qquad (35)$$

But $V(\underline{K} + e_0) = (\log C)/d - h_0\int^{\infty}(\underline{K} + e_t)^2 e^{-dt}$,
which, on using equation (35) and ignoring the square of e_0, yields

$$V(\underline{K} + e_0) \approx (\log C - h\underline{K}^2)/d - 2h\underline{K}e_0/(?+d). \qquad (36)$$

From equations (34) and (36), we conclude that

$$p(\underline{K}) = [dV(K)/dK]_{K=\underline{K}} = -2h\underline{K}/(d+?-2b\underline{K}/(1+\underline{K}^2)^2) < 0. \qquad (37)$$

Equation (37) is the shadow price of phosphorus in the lake column.

Notice that the above argument wouldn't work at $C = C^*$ or C^{**}. $V(\underline{K})$ is discontinuous at C^{**} if $\underline{K}$ is oligotrophic. (However, it posseses a left-derivative at C^{**}.) Moreover, $V(\underline{K})$ is discontinuous at C^* if $\underline{K}$ is eutrophic. (However, it possesses a right-derivative at C^*.) Shadow prices remain useful objects in a non-convex world, even if the locations of the bifurcation points C^* and C^{**} are known with certainty.

8. Extensions

In this section we extend the results that were obtained in Section 6, by considering in turn, population change, technological and instititutional change, and uncertainty.

8.1 Population Change

How does demographic change affect the index of sustainable development? To answer this, we have to determine how population change influences the drift term $(\partial V_t/\partial t)$ on the right hand side of equation (12). An alternative is to regard population as a capital asset. Once we do the latter, what would seem to be a non-autonomous resource allocation mechanism reduces to an autonomous one (Arrow *et al.*, 2003b).

8.1.1 Theory

To illustrate, we adopt a natural extension of Harsanyi (1955), by regarding social welfare to be the average welfare of all who are ever born. This form of "dynamic average utilitarianism" has been modelled by Dasgupta (2001a, [2004]) in the following way:

Let N_t be population size at t and $n(N_t)$ the percentage rate of change of N_t.[40] For notational simplicity, we ignore intragenerational inequality and changes in the age composition of the population. Let c_t denote per capita consumption at t. Therefore, if C_t is aggregate consumption, $c_t = C_t/N_t$. Assume as before that labour is supplied inelastically in each period. Current utility of the representative person is $U(c_t)$ and social welfare is,

$$V_t = {}_t\int^{\infty} N_t U(c_t) e^{-d(t-t)} dt / {}_t\int^{\infty} N_t e^{-d(t-t)} dt.^{41} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (38)$$

In order to ensure that V_t is well-defined, assume $d > {}_0\int^t (n(N_t)dt)/t$ for large enough t. Let K_{it} denote the stock of the ith type of capital good and write $k_{it} = K_{it}/N_t$. Let $\mathbf{k}_t$ be the vector of capital stocks per head. The state variables are therefore $\mathbf{k}_t$ and N_t. Assume a to be autonomous. Then equation (38) implies that

$$V_t = V(\mathbf{k}_t, N_t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (39)$$

Let the numeraire be utility. Define $v_t = \partial V_t/\partial N_t$. It is the contribution of an additional person at t to social welfare. v_t is the shadow price of a *person* (as distinct from the shadow price of a person's human capital). Let p_{it} denote the shadow price of k_{it}. Differentiating (39) with respect to t gives us

$$dV_t/dt = S_i p_{it} dk_{it}/dt + v_t dN_t/dt \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (40)$$

The right hand side of equation (40) is net investment, inclusive of the value of the change in population size. It generalizes equation (12). We conclude that Proposition 2 remains valid, so long as wealth comparisons mean comparisons of wealth *per capita*, adjusted for demographic changes.

Little is known of the circumstances where the adjustment term $(v_t dN_t/dt)$ is not negligible, but at the same time can be estimated in a simple way. It is easy enough, however, to locate conditions under which the term vanishes. Suppose (i) $n(N_t)$ is independent of N_t; (ii) all the production processes are linear; and (iii) $c_t = c(k_t)$, which means that under a, *per capita* consumption is not a function of population size. In such circumstances $V_t = V(k_t)$; that is, it is independent of N_t. (Effects of population change on V work through capital assets *per capita*.) This means that

$$dV_t/dt = S_i p_{it} dk_{it}/dt \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (41)$$

The finding can be summarised as

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[40] If Nt is a logistic function, n(Nt) = A(N*-Nt), where A and N* are positive constants.

[41] Notice that the social welfare ordering of economic programmes commencing at t is the same under dynamic average utilitarianism as it would be under dynamic total utilitarianism (i.e., expression (38) without the denominator; as in Mirrlees, 1967, and Arrow and Kurz, 1970). This is because the denominator is a constant, unaffected by choice of policy at t. However, as criteria for sustainable development, the formulations differ (Arrow *et al*., 2003b). This should not be seen as a paradox: optimality and sustainability are different notions

Proposition 7: If (i) $n(N_t)$ is independent of N_t, (ii) all the production processes are linear, and (iii) $c_t = c(k_t)$, then social welfare is sustained at a point in time if and only if the shadow value of the changes in per capita capital assets at that instant is non-negative.

8.1.2 Application

The conditions underlying Proposition 7 are too strong for comfort. Nevertheless, it is tempting to use equation (41) as a first approximation to equation (40). A large number of village level studies in South Asia and sub-Saharan Africa have uncovered that the local natural resource base has declined amidst growing populations in what continue to remain, broadly speaking, biomass-based economies.[42] Wealth *per capita* in those villages would appear to have declined. But what about the national level? Even if a nation's natural resource base were to decline, its wealth per capita would increase if the decline were more than compensated by increases in manufactured and human capital.

Dasgupta (2001a, [2004]) used Proposition 7, on data provided by Hamilton and Clemens (1999), in order to assess whether the world's poorest regions have enjoyed sustainable development in the recent past. The regions considered were sub-Saharan Africa, China, and the countries of the Indian sub-continent (South Asia). Taken together, those regions are inhabited by more than 3 billion people and are home to the bulk of the world's 1 billion poorest. They are also among the regions that have experienced the largest growth in population in recent decades.

Hamilton and Clemens (1999) had offered estimates of annual inclusive investment during the period 1970-1993 for a large number of countries.[43] There is much awkwardness in the steps the authors took to arrive at estimates of shadow prices. Their accounts are also incomplete. For example, among the resources making up natural capital, only commercial forests, oil and minerals, and the atmosphere as a sink for carbon dioxide were included. Not included were fresh water, forests as agents of carbon sequestration, fisheries, air and water pollutants, soil, and biodiversity. So there is an undercount, possibly a serious one. Such failings, however, are to be expected in pioneering empirical work. Moreover, one has to start somewhere.
In their work on the sources of national economic growth during 1965-1994, Collins and Bosworth (1996) had found the "residual" to have been -0.6 percent per year in sub-Saharan Africa, 0.8 percent per year in South Asia, and 1.1 percent per year in East Asia. If we interpret the residual to represent exogenous changes in knowledge and institutions, its influence on movements in social welfare (Proposition 1) would be reflected in the drift term ($\partial V_t/\partial t$) in equation (12). Nevertheless, Dasgupta (2001a, [2004]) assumed $\partial V_t/\partial t$ to have been zero in those regions. The justification he offered was that the figures for inclusive investment in Hamilton and Clemens (1999) are in all probability significant underestimates, and that figures for the residual in Collins and Bosworth (1996) - low as they are in South Asia - are nevertheless likely to be overestimates (see Section 8.2).

The first column of figures in the accompanying table (taken from Dasgupta, 2001a, [2004]) provides annual rates of growth of population over the period 1965-96 in the countries and regions in question. Notice that all but China experienced rates of growth in excess of 2 percent a year, sub-Saharan Africa and Pakistan having grown in numbers at nearly 3 percent a year. The second column of the table contains estimates of annual rates of change in wealth per head during 1970-1993. The striking message is that in all but China there was a decumulation in *per capita* wealth. Moreover, comparing the figures in the first two columns, it may be infered that during the

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[42] See, for example, the references in footnote 6.
[43] What we are calling inclusive investment was called "genuine saving" by Hamilton and Clemens.

period in question, Bangladesh and Nepal became poorer in the aggregate, not just on a *per capita* basis. In contrast, the other regions accumulated wealth in the aggregate. However, wealth accumulation did not keep pace with population growth in India, Pakistan, and sub-Saharan Africa. All this may not be a surprise in the case of sub-Saharan Africa, which is widely known to have regressed in terms of most economic indicators; but the figures for Bangladesh, India, Nepal, and Pakistan should cause surprise. Only China has accumulated wealth in excess of population growth. However, since the Hamilton-Clemens estimates of net investment do not include soil erosion or urban pollution, both of which are thought by experts to be especially problematic in China, the figure for China could be an overestimate. On the other hand, the residual in China was not negligible: in excess of 1 percent per year. So it is unclear in which direction a bias has been created in the estimate for China by the neglect of the drift term ($\partial V_t/\partial t$) in equation (12).

It should be emphasised that negative figures for changes in wealth *per capita* over time in South Asia and sub-Saharan Africa do *not* signal that people in those regions have been consuming too much! In imperfect economies it is possible to raise both consumption and inclusive investment.

How do changes in *per capita* inclusive wealth compare with changes in conventional measures of economic welfare? The third column of the table contains figures for the rate at which GNP per head changed during 1965-96; and the fourth column records whether the change in the United Nations' Human Development Index (HDI) over the period 1970-1995 was positive or negative.

Notice that our assessment of long-term economic development in the Indian sub-continent would be misleading if we were to rely on growth rates in per capita GNP as the index of development. Pakistan, for example, would be seen as a country where GNP per head grew at a healthy 2.7 percent a year, implying that the index doubled in value between 1965 and 1993. The corresponding figure in the second column implies though that the average Pakistani became poorer by a factor of about 1.5 during that same period.

Bangladesh is recorded as having grown in terms of *per capita* GNP at 1 percent a year during 1965-1996. The figure in the second column of the table implies that at the end of the period the average Bangladeshi was only about half as wealthy as she was at the beginning.

The case of sub-Saharan Africa is of course especially depressing. At an annual rate of decline of 2 percent in wealth *per capita*, the average person in the region became poorer by nearly a factor of two. The ills of sub-Saharan Africa are routine reading in today's newspapers and magazines, but the ills are not depicted in terms of a decline in wealth. The table suggests that sub-Saharan Africa has experienced a substantial decline in its capital assets over the past three decades.

What of the Human Development Index (HDI)? As the second and fourth columns of the table show, HDI offers a picture that is a near opposite to the one we should obtain when judging the performance of poor countries. The Human Development Index misleads even more than GNP.

The figures in the table for changes in wealth per capita are rough and ready and one should not regard them with anything like the certitude that we have developed over the years for international statistics on GNP and the demographic and morbidity statistics of poor countries. The estimates reported in the table are a first cut at what is an enormously difficult set of exercises. But the figures, such as they are, show how accounting for Nature can make for substantial differences to our conception of the processes of economic development.

8.2 Technological and Institutional Change

In a more comprehensive investigation, Arrow *et al.* (2004) have derived a procedure for converting figures for the residual into figures for the drift term ($\partial V_t/\partial t$) on the right hand side of equation (12). The authors used data on inclusive investment published in World Bank (2002) and estimates of the residual in the world's poorest regions, the Middle East, and the United States (US) and the United Kingdom (UK) from Klenow and Rodriguez-Clare (1997), to arrive at figures for the average annual rate of change in wealth *per capita*, at constant prices, during the period 1970-2001.

As noted earlier, the residual was in fact negative in sub-Saharan Africa, a reflection of institutional regress there. Consistent with Dasgupta's finding, Arrow *et al*. (2004) found that social welfare declined in sub-Saharan Africa during the period in question. They showed that the Middle East also experienced a decline in social welfare, owing in large measure to a decline in their oil wealth, unmatched by the accumulation of human capital and foreign assets. The US and UK were found to have enjoyed a growth in social welfare: the drift term ($\partial V_t/\partial t$) was positive and wealth *per capita* had increased in both countries. China was found to have enjoyed a huge annual percentage increase in wealth *per capita* (over 7 percent per year), the contribution of the drift term being enormous. The authors found that Bangladesh and Pakistan had experienced a small annual decline in wealth *per capita* during 1970-2001; but, encouragingly, they found that India and Nepal had enjoyed a *small increase* in social welfare (about 0.5 percent per year). The latter finding is at variance with the corresponding estimates in Dasgupta (2001a, [2004]), which, as we noted in Section 8.1, had found a decline in social welfare there. There are two reasons why the findings in Dasgupta (2001a, [2004]) differ from those in Arrow *et al*. (2004). First, the former publication ignored the residual, whereas the latter incorporated it in their estimate; and second, the periods under study were not the same in the two studies. In any event, the fact that one neglected the residual, while the other included it, can be regarded as constituting a sensitivity analysis of the recent macroeconomic history of South Asia.

This said, the figures for growth in wealth *per capita* in Arrow *et al*. (2004) are most likely to be over-estimates. To see why, recall that the typical exercise in growth accounting postulates that aggregate output (Y) is a function of manufactured capital (K), labour force participation (L), and human capital (H). One specification would be

$$Y_t = A_tF(K_t, H_tL_t), \qquad (42)$$

where A_t is a scale factor, reflecting total factor productivity, while F is a constant returns to scale function of K and HL (perhaps even of the Cobb-Douglas form).

Differentiating both sides of equation (42) with respect to time, re-arranging terms, and writing by $g(X_t) = (dX_t/dt)/X_t$ for variable X_t; by $J_t = H_tL_t$; by $s_K = K_tF_K/F$ (the "share" of factor K in aggregate output); and by $s_J = J_tF_J/F$ (the "share" of factor J in aggregate output); we have

$$g(Y_t) = g(A_t) + s_Kg(K_t) + s_J(g(H_t) + g(L_t)). \qquad (43)$$

The idea now is to obtain time series of $g(Y_t)$, $s_Kg(K_t)$, and $s_J(g(H_t) + g(L_t))$ and then to arrive at an estimate of $g(A_t)$ from equation (43). $g(A_t)$ is the residual.

One problem with the function F in expression (42) is that it leaves out the flow of Nature's services in production. Admittedly, ecosystem services are hard to estimate, but energy use could be used as a surrogate. Now suppose that the use of Nature's services in production has increased over a period. That increase would be missing from the latter two terms on the right hand side of equation (43). Therefore, it would be regarded as being a part of the residual. But this would be more than just ironic: a nation could in principle step up the rate at which its natural resources are mined and then claim on the basis of its growth accounts that the figures reflect increases in technological progress and improvements in its institutions!

8.3 Uncertainty

How should uncertainty be accommodated? The theory of choice under uncertainty, in its normative guise, remains the *expected-utility* theory. There is a large and still-growing experimental literature attesting to the fact that in laboratory conditions people don't choose in accordance with the theory (Bell *et al*., 1988). But here we are concerned with normative questions. That the choices we make in the laboratory don't conform to expected utility theory does not mean that the theory is not the correct ethical basis for evaluating policy alternatives or assessing where or not the economic programme being pursued reflects sustainable development.
When applied to the valuation of uncertain consumption programmes, probabilities are imputed to future events. The probabilities are taken to be subjective, such as those involving long-range climate, although there can be objective components. Let E_t denote expectations at t. Assume that population is constant. Recalling expression (8), social welfare can then be expressed as,

$$V(\mathbf{K}_t) = E_t\left(\int_t^{\infty} U(C_t(a))e^{-d(t-t)}dt\right). \qquad (44)$$

A deficiency in the figures for changes in wealth reported in Section 8.1 is that they are point estimates. However, given that there are vast uncertainties associated with any such estimate, there is the possibility that changes in wealth *per capita* have been negative even though the central estimates themselves are positive.

In considering the risks associated with degradation of natural capital, it is worth recalling that the biophysical impacts of such degradation can be highly nonlinear: the impacts could be small over a considerable range, but then become immense once a critical threshold is reached. As we noted in the extended example in Section 5, crossing the threshold leads to a bifurcation, where the natural system's characteristics change fundamentally. Such non-convexities in ecological processes imply that the distribution for changes in wealth *per capita* may be highly skewed - the downside risks associated with the loss of certain forms of natural capital may be substantial. Estimates of changes in *per capita* wealth reported in Sections 8.1.2 may be interpreted as representing the most-likely scenario; therefore, they do not capture the downside risks associated with the depletion of natural capital. To the extent that societies are risk-averse, it is important to award additional weight to the negative scenarios. Doing so would imply lower estimates of changes in *per capita* wealth.

Models of global climate indicate that bifurcations can occur if the rates and magnitude of greenhouse gases increase sufficiently. However, the threshold points are not known. It is clear from paleoclimatic history, though, that such events were common. Mastrandrea and Schneider (2001) have employed a linked climate-economy model to investigate the future possibilities of climate thresholds of this type, and have assessed the implications for climate policy.

Uncertainties regarding environmental events in the very distant future are sometimes called "deep" uncertainties, the qualification being taken to mean that it may not be possible to assign even subjective probabilities to those events. This is another way of saying that when there are deep uncertainties, it is difficult to know what one should choose, or how one should organise one's thoughts regarding what to choose. Examples frequently mentioned are risks associated with global climate change. There are decision theories (e.g., Bewley, 1989) that offer reasons why we ought to be reluctant to undertake activities involving unestimable risks. They suggest that the *status-quo* should assume a favoured status, which is the hallmark of what many refer to as the *precautionary principle* (e.g., Appell, 2001), frequently espoused by environmentalists. Such theories would appeal to someone who feels that it is easier to prevent environmental damage than to repair it subsequently. The theory gives expression to the demand that, in evaluating radically new technology (e.g., biotechnology), the burden of proof ought to shift away from those who advocate protection from environmental damage, to those supporting the new technology.

The problem with such theories is that they are supremely conservative. Admittedly, even expected utility theory can be made ultra-conservative if we adopt an infinite aversion to risk - which is to say that the elasticity of $U'(C)$ in expression (8) is infinity - and imagine that the worst that can happen under any change in policy is worse than the worst that can happen under the *status-quo*. But it is difficult to justify such an attitude: we wouldn't adopt it even in our personal lives. At the moment we don't have a theory, normative or otherwise, that covers long-term environmental uncertainties in a satisfactory way.

9. Concluding Remarks

In this article we have surveyed those recent developments in environmental and resource economics that have been prompted by a puzzling cultural phenomenon of recent years: one group of scientists (usually natural scientists) sees in humanity's current use of Nature's services symptoms of a deep malaise, even while another group of scientists (usually economists) documents the fact that people today are on average better off in many ways than they had ever been (so why the gloom?).[44] The developments surveyed here have reconciled some of the claims and counter claims, by showing that the warring protagonists have frequently talked past one another. We do not wish to suggest that disagreements between the two groups will not arise once they adopt the technical vocabulary recently developed by environmental and resource economists; but the disagreements that would continue to arise would be over interpretations of evidence (e.g., about the costs and benefits of doing something today about global warming), they would not be over what to disagree about!

9.1 Shadow Prices and Wealth Estimates in National Accounts

By reconstructing welfare indicators to account for our use of natural resources, recent developments in environmental and resource economics have seen an enlargement of the scope of both micro- and macro-economic reasoning. Extending modern welfare economics, it has been shown that discussions on intergenerational welfare should be about institutions and policies that bring about changes and movements in *wealth*, where by an economy's wealth we mean the social worth of its entire set of capital assets, including not only manufactured and human capital, but also knowledge and natural capital. Estimates of movements in wealth *per capita* in a number of countries and regions since the early 1970s were reported in Section 8. They suggest that, while industrialised countries, such as the United States and the United Kingdom, have accumulated wealth *per capita*, sub-Saharan Africa and the Middle East have suffered a decline. The Indian sub-continent would appear to be a border-line case. But these are early days, and much more work needs to be done toward estimating shadow prices and

[44] The disagreement is mirrored in popular writings. See, for example, McNeil (2000) and *The Economist* ("Environmental Scares: Plenty of Gloom", 20 December 1997) for differing perspectives. For commentaries on the latter article by a group of ecologists and economists, see the symposium in *Environment and Development Economics*, 1998, Vol. 3, Part 4.

using them for the preparation of comprehensive capital accounts before we can be reasonably confident of the recent macroeconomic history of South Asia.

We are under no illusion that estimating wealth is going to prove a simple task. Markets for environmental natural resources are often at best imperfect, at worst are non-existent. But that stricture offers no ground for pretending that natural capital is in infinite supply. To pretend thus, while refining the ways GNP is estimated so as to better record the progress of nations, is to be the proverbial man in the dark, seeking to retrieve his keys from under the lamp post even while knowing full well that they are not there.

9.2 Poverty and the Natural Resource Base

The developments in environmental and resource economics surveyed here have also offered us a language in which to study rural economies in the world's poorest regions. Aggregate statistics at the national level can suppress information pertaining to local natural resource bases. Modern environmental and resource economics has shown that the intellectual disputes among those economists who see signs of economic betterment in increases in GNP per head (or improvements in the United Nations' Human Development Index) and those who see the persistence of acute poverty in large parts of the poor world have arisen in part because the protagonists have talked past one another. In Section 4 we reported recent work on village economies and on the importance of the local resource base there. We found that the study of village based, non-market institutions can help to explain how certain groups of people may remain in poverty (possibly even suffer a worsening in their circumstances), even while others thrive as markets grow elsewhere. The spatial character of ecosystems (and thence, of rural economies) was stressed. The findings suggest that there is much scope for further work in the ways in which the spatial heterogeneity of natural capital affects the prospects facing rural economies.[45]

9.3 Growth Theories and Resource Constraints

Contemporary models of economic growth are by and large dismissive of the importance of Nature. In their extreme form, growth models assume a positive link between the creation of ideas (technological progress) and population growth in a world where the natural-resource base comprises a fixed, indestructible factor of production. The models do involve positive feedback, but of a Panglossian kind.[46]

There is a great deal to commend in contemporary growth models, but recent developments in environmental and resource economics suggest that we should be circumspect in our enthusiasm for them. Nature is not fixed and indestructible, but consists of degradable resources (agricultural soil, watersheds, fisheries, and sources of fresh water; more generally, ecological services). It may be sensible to make the wrong assumption for studying a period when natural resource constraints did not bite, but it may not be sensible when studying development possibilities in poor countries today. The latter move would be especially suspect if no grounds were offered for supposing that technological progress can be depended upon indefinitely to more than substitute for an ever increasing loss of the natural-resource base. Moreover, as was noted in Sections 1-4, ecological resources are frequently underpriced. This means that the direction of technological change is biased toward an excessive reliance on the natural resource base. As that base shrinks, it may prove harder and harder to find ways of substituting our way out of the problem of resource scarcity.

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45 Tilman and Kareiva (1997) is an excellent collection of articles on spatial ecological dynamics.
46 Kremer (1993) develops such a model to account for 1 million years of world economic history.

In any event, it is not prudent to adopt a point of view that places such enormous burden on an experience not much more than two hundred and fifty years old. Extrapolation into the past is a sobering exercise: over the long haul of history (a 5,000 years stretch, say, upto about two hundred years ago), economic growth even in the currently-rich countries was for most of the time not much above zero.[47]

The foregoing remarks bear on the aggregate economy. At a more micro level, we noted in Sections 3-5 that positive feedback in ecological (including individual metabolic) pathways are reasons why the prospects of economic betterment among the world's poorest are bleaker than among the rich. The non-convexities the poor face can be a reflection of their inability to obtain substitutes for depleted natural resources. Resource depletion for the poor can be like crossing a threshold: their room for maneouver is circumscribed hugely once they cross. In contrast, the rich can usually "substitute" their way out of problems.

The simultaneous presence of two types of positive feedback - one enabling many to move up in their living standard, the other keeping many others in poverty - may explain the large scale persistence of absolute poverty in a world that has been growing wealthier on average by substituting manufactured and human capital for natural capital. For human well-being, policies matter, as do institutions, but the local ecology matters too. If we have stressed the positive feedback mechanisms that operate at the downside of life, it is because degradation of the natural-resource base is felt first by the poor, not the rich.

47 See Fogel (1994), Johnson (2000), and especially Maddison (2001). The claim holds even if the past two hundred years were to be included. Here is a rough calculation: World per capita output today is about 5000 US dollars. The World Bank regards one dollar a day to be about as bad as it can be. People wouldn't be able to survive on anything substantially less than that. It would then be reasonable to suppose that 2000 years ago per capita income was not much less than a dollar a day. So, let us assume that it was a dollar a day. This would mean that per capita income 2000 years ago was about 350 dollars a year. Rounding off numbers, this means, very roughly speaking, that per capita income has risen about 16 times since then. This in turn means that world income per head has doubled every 500 years, which in its turn means that the average annual rate of growth has been about 0.14 percent per year, a figure not much in excess of zero, which is what we have alluded to in the text.

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APPENDIX 1

Economic Change: 1970-93

	g(L)[a]	g(W/L)[b]	g(Y/L)[c]	? (HDI)[d]
Bangladesh	2.3	-2.40	1.0	+ve
India	2.1	-0.50	2.3	+ve
Nepal	2.4	-2.60	1.0	+ve
Pakistan	2.9	-1.70	2.7	+ve
Sub-Saharan Africa	2.7	-2.00	-0.2	+ve
China	1.7	1.09	6.7	+ve

[a] g(L): average annual percentage rate of growth of population, 1965-96.

[b] g(W/L): average annual percentage rate of change in wealth per head at constant prices. Adapted from Hamilton and Clemens (1999) and from data provided in personal communication by Katie Bolt of the World Bank.

[c] g(Y/L): average annual percentage rate of change in GNP per head, 1965-96.

[d] ? (HDI): sign of change in the United Nations' Human Development Index, 1970-1995.

Source. Dasgupta (2001a, [2004]).