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Chapter 5
Natural Capital and Sustainable Development

Contents

We refer to environmental resources as natural capital, a practice that allows us to place them on a par with other forms of tangible capital assets, such as roads, buildings, vehicles, and machinery; and with such intangible capital assets as knowledge, skills, health, and institutions.

Natural capital can be of direct use (as consumption goods, such as fruit and honey), or of indirect use as inputs in production (oil and natural gas; microbes that regulate diseases), or of both direct and indirect use (clean air; fresh water). The value of natural capital could be utilitarian (a source of food; a keystone species) - economists call that its use-value; it may be aesthetic (places of scenic beauty); it may be intrinsic (primates, sacred groves); or it could be all those things (biodiversity). Natural capital's worth to us could be from the products we are able to extract from it (timber; gum; honey; leaves and barks containing medicinal compounds), or from its presence as a stock (forest cover), or from both (watersheds). The stock could be an index of quality (air quality) or quantity. Quantity is sometimes expressed as a pure number (population size); in various other cases it is, respectively, (bio)mass, area, volume, depth. But even quality indices are often based on quantity indices (as in, "parts per cubic centimetres" for measuring atmospheric haze).

We view natural capital here in an inclusive way. At one extreme are fossil fuels. Economists call them "exhaustible resources" because, by the workings of the Second Law of Thermodynamics, each unit of a fossil fuel used in production is lost forever. More generally, natural resources are "self"-regenerative. Handled with care, they can be put to use in a sustained way, but get depleted if the rate at which they are exploited exceeds their rate of regeneration. The central problem in sustainability science is to uncover ways by which a literally indeterminate number of interlocking natural processes that shape self-regenerative resources can be managed so as to enable Humanity to flourish indefinitely.

In recent years ecologists have drawn attention to the services Humanity enjoys from one broad class of natural capital assets: ecosystems (Daily, 1997). As ecosystems are a mesh of humans and natural resources interacting with one another at various speeds and across various spatial scales, the notion of an ecosystem is usually dictated by the scope of the environmental problem being studied. A number of ecosystems have a global reach (the deep oceans), others extend over large land masses ("biomes", such as the Savannah and the tundra), some cover entire regions (river basins), many involve clusters of villages (micro-watersheds), while others are confined to the level of a single village (the village pond).

The Millennium Ecosystem Assessment (MEA, 2003) offered a four-way classification of ecosystem services: (i) provisioning services (food; fibre; fuel; fresh water); (ii) regulating services (protection against natural hazards such as storms; the climate system); (iii) supporting services (nutrient cycling; soil production); and (iv) cultural services (recreation; cultural landscapes; aesthetic or spiritual experiences). In Part III, where formal models of ecosystems are presented, we will see that the MEA classification can be unified for the purposes of quantitative reasoning. Here it is as well to note that cultural services and a variety of regulating services (such as disease regulation) contribute directly to human well-being, whereas others (soil production) contribute indirectly (by providing the means of growing food crops).

5.1 Nature as a Capital Asset

Viewing natural capital in an inclusive way allows us to develop a comprehensive language for sustainability science. We begin by studying four issues that appear regularly in public discussions on the state of the environment.

5.1.2 Pollution and Conservation

Environmental problems are frequently discussed in terms of "pollution", not conservation. There is no difference between the two however, because environmental pollutants are the other side of natural resources. In some cases the emission of pollutants amounts directly to a degradation of ecosystems (the effect of acid rains on forests); in others (wastes from pulp and paper mills), it means a reduction in environmental quality (deterioration of water quality), which also amounts to degradation of ecosystems (watersheds). Thus, for analytical purposes there is no reason to distinguish resource management from pollution management. Roughly speaking, "resources" are "goods", while "pollutants" (the degrader of resources) are "bads". Pollution is the reverse of conservation.[1]

The mirror-symmetry between conservation and pollution is illustrated by the atmosphere, which serves as both a source of nourishment and a sink for pollutants. The atmosphere is a public good: if the quality of the open atmosphere is improved, we all enjoy the benefits; and none can be excluded from enjoying those benefits.[2] However, unless public legislation says otherwise, the atmosphere is also a common pool for pollution. It's a pool into which everyone can discharge pollutants without having to pay. As the atmosphere is a public good, the private benefit from improving air quality is less than the social benefit. It follows that in the absence of collective action (e.g., public investment or public subsidy in cleaner technologies), there is underinvestment in air quality.

Now look at the reverse side of the coin. As the atmosphere is a pool into which pollutants can be deposited by us all, the private cost of pollution is less than the social cost. It follows that without collective action (e.g., the imposition of a pollution tax; quantity restriction per user; "cap-and-trade", which continues to be a much discussed social mechanism for controlling carbon emissions), there is excessive use of the pool as a sink for pollutants. Either

[1] This dual structure was developed in Dasgupta (1982).

[2] The two characteristics of the atmosphere just mentioned define "public goods": such goods have the property that (i) they are jointly consumable and (ii) no one can be excluded from consuming them.

way, the atmosphere suffers from "the tragedy of the commons".[3]

5.1.2 Luxuries vs. Necessities

Ecosystem services are not only intrinsically valuable, they also have functional worth. But scratch an economist and you are likely to find someone who regards natural capital as a luxury. It is commonly thought that, to quote an editorial in the UK's The Independent (4 December 1999), "... (economic) growth is good for the environment because countries need to put poverty behind them in order to care", or, to quote The Economist (4 December, 1999: 17), "... 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 quoted passages reflect an odd viewpoint. Producing as it does a multitude of ecosystem services, a large part of what Nature offers us is a necessity. Many of the services we obtain from natural capital are even "basic needs" (Chapter 4). Among the visible products are food, fibres, fuel, and fresh water. But many are hidden from view. Ecosystems maintain a genetic library, preserve and regenerate soil, fix nitrogen and carbon, recycle nutrients, control floods, mitigate droughts, filter pollutants, assimilate waste, pollinate crops, operate the hydrological cycle, and maintain the gaseous composition of the atmosphere (Chapter 3). A number of services filter into a global context, but many are geographically confined (Chapters 7 and 8). Human well-being and the state of our ecosystems are closely linked.

Ecosystems offer joint products. Wetlands recycle nutrients and produce purified water; mangrove forests protect coastal land from storms and are spawning grounds for fish; and so on. Unhappily, social tensions arise in those many cases where an ecosystem has competing uses (farms versus forests versus urban developments; forests versus agro-ecosystems; coastal fisheries versus aquaculture[4]). Dasgupta (1982, 1993) and Sachs, Gallup, and Mellinger (1998) (1998) traced the location of world poverty in part to the fact that the tropics harbour some of the most fragile ecosystems, including those that regulate disease. Carpenter et al. (2005) and Hassan, Scholes, and Ash (2005), which contain the first two sets of technical reports accompanying the Millennium Ecosystem Assessment, found that 15 out of the 24 major ecosystem services that the MEA examined are either already degraded or are currently subject to unsustainable use.

A resource can be a luxury for others even while it is a necessity for some. Consider watersheds, which nurture commercial timber, agricultural land, recreational opportunities, and both market and non-market products (gums, resin, honey, fibres, fodder, fresh water, and fuel-wood). Watershed forests purify water and protect downstream farmers and fishermen from

[3] The metaphor is due to Hardin (1968).

[4] See Tomich et al., eds. (2004), Tomich et al. (2004) and Palm et al. (2005); and Hassan, Scholes, and Ash (2005), respectively, on those tensions.

floods, droughts, and sediments. In tropical watersheds, forests house a significant quantity of carbon and are the major home of biodiversity. A number of products from watersheds are necessities for local inhabitants (forest dwellers, downstream farmers, and fishermen), some are sources of revenue for commercial firms (timber companies), while others are luxuries for outsiders (eco-tourists). Many benefits from watersheds accrue to nationals in the form of agricultural products and fibres, while others spill over geographical boundaries (carbon sequestration). So, while watersheds offer joint products (protection of biodiversity, flood control, carbon sequestration, household goods), they also provide potential services that compete against one another (commercial timber, agricultural land, biodiversity). Competition for Nature's services has been a prime force behind the transformation of ecosystems, a matter we studied earlier and will study further in Chapters 8 and 9. In Chapter 6 it will be seen that politics often intervenes to ensure that commercial demand trumps local needs, especially under non-democratic regimes. Governments in poor countries have been known to issue timber concessions in upstream forests to private logging firms, even while evicting forest dwellers and increasing siltation and the risk of floods downstream. Nor can the international community be depended upon to apply pressure on governments. When biodiversity is lost at a particular site, eco-tourists go elsewhere that has rich biodiversity on offer. So, international opinion is often at best tepid. In both examples, local needs are outflanked by outsiders' demands.

5.1.3 Irreversible Uses

Ecosystems are driven by interlocking non-linear processes that run at various speeds and operate at various spatial scales (Steffen et al., 2004). That is why ecosystems harbour multiple basins of attraction (Chapter 8). The global climate system is now a well known example. But small-scale ecosystems also contain multiple basins of attraction. And for similar reasons. So long as phosphorus run-off into a fresh water lake is less than the rate at which the nutrient settles at the bottom, the water column remains clear. But if over a period of time the run-off exceeds that rate, the lake collapses into a eutrophic state (Chapter 8). Usually, of course, the point at which the lake will collapse is unknown. That means the system is driven by non-linear stochastic processes.

When wetlands, forests, and woodlands are destroyed (for agriculture, urban extension, or whatever), traditional dwellers suffer. For them, and they are among the poorest in society, there are no substitutes. For others, there is something else, often somewhere else, which means there are substitutes. Degradation of ecosystems is like the depreciation of roads, buildings, and machinery - but with three big differences: (1) depreciation of natural capital is frequently irreversible (or at best the systems take a long time to recover; Chapter 8), (2) except in a very limited sense, it isn't possible to replace a depleted or degraded ecosystem by a new one, and (3) ecosystems can collapse abruptly, without much prior warning (Chapter 8). Imagine what would happen to a city's inhabitants if the infrastructure connecting it to the outside world was to break down without notice. Vanishing water holes, deteriorating grazing fields, barren slopes, and wasting mangroves are spatially confined instances of corresponding breakdowns among the rural poor in poor countries. In recent years we have also seen how an ecological collapse, such as the one that has been experienced in recent years in the Horn of Africa and the Darfur region of Sudan, can trigger rapid socio-economic decline (Homer-Dixon, 1999; Diamond, 2005; Collier, 2007). The range between a need and a luxury is thus enormous and context-ridden. Macroeconomic reasoning glosses over the heteregeneity of Earth's resources and the diverse uses to which they are put - by people residing at the site and by those elsewhere. Later in this book we confirm that GDP can grow at the expense of the lives of the poorest. Poverty and degradation of the local natural-resource base are tied to each other by politics and economics. We should not have expected it to be otherwise.

5.1.4 Substitution Possibilities

Environmental debates are often on the extent to which people are able to substitute one thing for another. Many believe that problems arising from the depletion of natural capital can always be overcome by the accumulation of manufactured capital, knowledge, and skills.[5] Others argue that Humanity has reached the stage where there are severe limits to further substitution possibilities among large numbers of natural resources and among resources and other forms of capital assets (Ehrlich and Goulder, 2007).

Four kinds of substitution help to ease resource constraints, be they local or global. First, there can be substitution of one thing for another in consumption (nylon and rayon substituting for cotton and wool; pulses substituting for meat). Secondly, manufactured capital can substitute for labour and natural capital in production (the wheel and double-glazing are two extreme examples). Thirdly, novel production techniques can substitute for old ones.[6] Fourthly, and for us here most importantly, natural resources themselves can substitute for one another (e.g., renewable energy sources could substitute for non-renewable ones). These examples point to a general idea: as each resource is depleted, there are close substitutes lying in wait, either at the site or elsewhere. If that idea were true, then, even as constraints increasingly bite on any one resource base, Humanity should be able move to other resource bases, either at the same site or elsewhere. The enormous additions to the sources of industrial energy that have been realized (successively, human and animal power, wind, timber, water, coal, oil and natural gas and, most

[5] Lomborg (2001) is an example. Macroeconomic growth theories are mostly built on economic models in which Nature makes no appearance. See below in the text.

[6] For example, the discovery of effective ways to replace the piston by the steam turbine (i.e., converting from reciprocating to rotary motion) was introduced into power plants and ships a little over 100 years ago. The innovation was an enormous energy saver in engines.

recently, nuclear power) are a prime historical illustration of this possibility.[7]

Humanity has been substituting one thing for another since time immemorial. Even the final conversion of forests into agricultural land in England in the Middle Ages was a form of substitution: large ecosystems were transformed to produce more food.[8] But both the pace and scale of substitution in recent centuries have been unprecedented. Landes (1969) has argued that the discovery of vast numbers of ways of substituting resources among one another characterized the Industrial Revolution in late eighteenth century. The extraordinary economic progress experienced in Western Europe and North America since then, and in East Asia more recently, has been another consequence of finding new ways to substitute goods and services among one another and to bring about those substitutions. That ecosystems are spatially dispersed has enabled this to happen. The ecological transformation of rural England in the Middle Ages probably reduced the nation's biodiversity, but it increased income without any direct effect on global productivity.

But that was then and there, and we are in the here and now. The question is whether it is possible for the scale of human activity to increase substantially beyond what it is today without placing undue stress on the major ecosystems that remain. The cost of substituting manufactured capital for natural resources can be high. Low-cost substitutes could turn out to be not so "low-cost" if the true costs are used in the accounting, rather than the costs recorded in the marketplace (see below). Depleting one type of natural capital and substituting it with another form of natural capital or with a manufactured capital is frequently uneconomical.

5.2 Conflicting Views on Economic Prospects

Economic growth is a good thing. It may not buy happiness, but it usually purchases a better quality of life (Chapter 4). Table 4.1 showed that growth in real GDP per capita usually comes hand in hand with improvements in the way people are able to live. But can economies grow indefinitely, or are there limits to growth? To put the question in a more contemporary form, is continual growth in real GDP compatible with sustainable economic development, or would economies that concentrated on GDP growth face the big crunch one day?

The question is several decades old. If discussions on it continue to be shrill, it is because two opposing empirical perspectives have shaped them. On the one hand, if we look at specific examples of natural capital (fresh water, ocean fisheries, the atmosphere as a carbon sink - more generally, ecosystems), there is strong evidence that the rates at which we are currently utilizing them are unsustainable. During the 20th century world population grew by a factor of four to more than 6 billion, industrial output increased by a multiple of 40 and the use of energy by 16,

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[7] But these shifts have not been without unintended consequences. Global climate change didn't feature in economic calculations until very recently.

[8] Forests in England had begun to be denuded earlier, by Neolithic Britons and the Romans.

methane-producing cattle population grew in pace with human population, fish catch increased by a multiple of 35 and carbon and sulfur dioxide emissions by 10. The application of nitrogen to the terrestrial environment from the use of fertilizers, fossil fuels, and leguminous crops is now at least as great as that from all natural sources combined. The scale of our presence on Earth is so huge that Humanity has created an unprecedented disturbance in Nature in a brief period of a century or so.

On the other hand, it is often argued that just as earlier generations in the West had invested in science and technology, education, and machinary so as to bequeath to their descendents the ability to achieve high income levels, the current generation is now in turn making investments that will assure still higher living standards in the future. It has been argued as well that time series of prices of marketed natural resources, such as minerals and ores, have been so flat that there isn't any cause for alarm.[9] Moreover, economic growth has allowed more people to have access to potable water and enjoy better protection against water- and air-borne diseases (Chapter 4). The physical environment inside the home has improved beyond measure with economic growth (cooking in the Indian sub-continent continues to be a major cause of respiratory illnesses among women). It has been argued as well that, as natural capital can be so moved round today, dwindling resources in one place can be met by imports from another. Intellectuals and commentators use the term "globalization" to imply that location per se doesn't matter. That optimistic view emphasizes the potential of capital accumulation and technological improvements to compensate for environmental degradation. It says that continual economic growth, even in the form and shape it has taken so far, is compatible with sustainable development. That probably explains why contemporary societies are obsessed with cultural survival and are on the whole dismissive of any suggestion that we need to find ways to survive ecologically.

There are probably deep psychological reasons why we are often ambivalent about environmental matters.[10] The various causes behind contemporary environmental degradation pull in different directions and are together not unrelated to an intellectual tension between the concerns people share about global climate change and international fisheries that sweep across the globe, and about those matters (such as the decline in firewood or water sources in rural areas in the world' poorest regions) that are specific to the needs and concerns of village communities. Environmental problems present themselves differently to different people. In part, it is a reflection of the tension we have just noted and is a source of misunderstanding of people's attitudes. Some people identify environmental problems with population growth, while others

[9] Barnett and Morse (1963) is a classic study. They found that time-series of the market prices of minerals and fossil fuels have been relatively flat. Slade (1982) revisited the question and found some increase in the then recent prices.

[10] For a searching discussion of this, see Ehrlich and Ehrlich (1996, 2004).

identify them with wrong sorts of economic growth. Then there are those who view them through the spectacle of poverty. Each of these visions is correct. There is no single environmental problem; rather, there is an innumerable collection of them.

On the other hand, it is all too clear from the evidence that economic growth itself has brought with it improvements in the quality of a number of environmental resources. The positive links between economic growth and certain environmental qualities (indoor atmosphere, water quality) often go unnoted by environmentalists in the West. We would guess that this lacuna is yet another reflection of the fact that it is all too easy to overlook the enormous heterogeneity of natural capital, ranging as it does from the atmosphere, oceans, and landscapes, to water-holes, grazing fields, and sources of fuelwood. This heterogeneity should be kept in mind.

5.3 Property Rights to Natural Capital

If natural capital were really becoming scarcer, wouldn't their market prices have risen? And aren't price increases the only reliable sign of growing scarcity?

The answer is "no". It could be that various kinds of natural capital are becoming scarcer even while prices in the market don't register that fact; which is another way of saying that markets don't provide us with the right incentives to economise on our use of Nature's services. The question arises: Why don't market prices reflect Nature's scarcity value?

The answer is that if prices are to reflect the social scarcities of goods and services, markets must function well. But for many types of natural capital - most especially ecological capital - markets not only don't function well, often they don't even exist. In some cases markets don't exist because relevant economic interactions take place over large distances, making the costs of negotiation among interested parties too high (the effects of upland deforestation on downstream farming and fishing activities); in other cases they don't exist because the interactions are separated by large temporal distances (the effect of carbon emission on climate in the distant future, in a world where forward markets don't exist because future generations are not present today to negotiate with us). The general reason markets for ecological services don't exist is that private property rights to natural capital are frequently impossible to define - let alone enforce. An overarching reason for the latter is that many "species" of natural capital are mobile. Birds and insects fly, rivers flow, fish swim, the winds carry, gases and particulates diffuse in air and water, and even earthworms are known to travel. The migratory nature of resources prevent their markets from forming, because it isn't possible for someone acting singly to lay claim to it.

Extreme examples of resources whose markets don't exist are the atmosphere, aquifers, and the open seas. Such resources are open to all, which is why they are called "open access" resources. They experience the "tragedy of the commons".

Each of the above examples points to a failure to have secure private property rights to natural capital. We can state the problem in the following way: ill-specified or unprotected property rights prevent markets from forming or make markets function wrongly when they do form.

But what about non-market institutions? To study them, we expand the notion of property rights to include communal property rights (over common property resources such as coastal fisheries or village tanks) and public or State property rights (over forest lands). At an extreme are "global property rights", a concept that is implicit in current discussions on climate change. But the idea isn't new. That humanity has collective responsibility over the state of the world's oceans used to be explicit in the 1970s, when politicians claimed that the oceans are a "common heritage of mankind".

Many of the reasons markets don't function well are applicable also to non-market institutions. We study them in detail Chapter 6. But it is as well to note here that environmental problems arise because of institutional failure, not simply market failure. The failure could most certainly be an absence of markets for ecological services; but it could be that of a group of nations unable to agree on a common fisheries policy in the seas, or it could be the State and private industry riding roughshod over forest inhabitants; it could be the local community, whose norms of behaviour over the use of their local commons have collapsed; or it could be failure of the household, where the dominant male insists on growing fruit trees (the fruit can be sold in the market to which the female doesn't have easy access), rather than trees that would supply the woodfuel the female is expected to gather from the receding woodlands. The consequences of malfunctioning institutions are resource allocation failures among contemporaries and across the generations. To identify environmental problems as "market failure", as is commonly done in environmental economics (e.g., Baumol and Oates, 1975; Stern, 2006), is a mistake. The general conclusion should be that the use of natural capital comes allied to externalities, an ubiquitous phenomenon we study in detail in Chapter 6. Here we merely note that externalities are the effects of activities on those who were not a party to the negotiations that led to those activities.

Historically, societies everywhere have tried to devise collective property rights to mobile capital, be they communal rights over local resource bases (micro watersheds; coastal fisheries) or international rights over global resources (shipping in international waters; traffic in air space). Unhappily, agreements over the use of natural capital of critical importance would appear to be currently beyond our collective reach (Chapter 6). And even when they are reached, problems of enforcement often overwhelm agreements, leading to warfare and strife. Humanity is in need of a robust ethical framework for dealing with Nature because collective agreements are needed. Mutual trust in our relationships with one another assumes enormous significance in the economics of Nature.

Institutional failure in the use of natural resources means that they are underpriced in the market. Which is why, tracking time series of the market prices of minerals and fossil fuels in order to judge whether we face increasing resource scarcity is a bad move. Mining, smelting, and transporting minerals and ores involve the use of other types of natural capital (e.g., sinks into which industrial effluents are deposited) for which payment is not made. That is another example of "externalities". The social cost of those industrial operations could be rising even while the mineral prices remain flat or perhaps even decline. The right thing to do is to recognise that the use of natural capital is implicitly subsidized by people who suffer from those externalities.

At the global level what is the annual subsidy? One calculation suggested that it is 10% of annual global income (Myers and Kent, 2000). Our reading is that the margin of error in that estimate is very large. But it's the only global estimate we have. Much the most reliable studies are those that look at "small" problems (people exploiting a fishery, a wetland, a coral reef, a water hole, a mangrove, a grazing field, a woodland, and so forth). The most promising route to a better understanding of the socio-ecological processes that shape our macroeconomies is to aggregate those small problems. From the global perspective, each of those innumerable small problems may indeed be "small"; but when you add them up, the sum is not small. Recent empirical work on the matter suggests that they can be very large (MEA, 2003).

Repetto et al. (1989) and Vincent and Ali (1997), respectively, estimated the decline in forest cover in Indonesia and Malaysia. They found that when deforestation is included, national accounts look quite different: net domestic saving rates are some 20-30% lower than recorded saving rates. In their work on the depreciation of natural resources in Costa Rica, the World Resources Institute some years ago found that the depreciation of three resources — forests, soil, and fisheries — amounted to about 10% of GDP and over a third of capital accumulation. The findings suggest that an economy could in principle enjoy growth in real gross domestic product (GDP) and improvements in the United Nations' Human Development Index (HDI) for a long spell even while its productive base shrinks.

Ominously, the under-pricing of natural capital filters down to influence research and development. The latter influences the character of technological change. Because Nature's services are underpriced in the market, innovators have little reason to economise on their use. We shouldn't be surprised when new technologies are rapacious in the use of natural capital.

5.4 Sustainable Development: Formalizations

Economic development should be evaluated in terms of its contribution to social well-being. As we should be interested not only in the well-being of the present generation, but also that of future generations, social well-being means intergenerational well-being (Chapter 4*). By an "economy" we mean any unit of activity we care to study. The unit ranges from a household at one extreme, to the world as a whole at the other. The analysis that follows does not depend on any particular specification of the "economy" under observation. However, national economies are frequently the units in socio-economic data published by international organizations on an annual basis. In developing the idea of sustainable development here, we follow that practice.

We noted earlier that there are two types of evaluation exercises. One prescribes, the other assesses. It was noted too that policy evaluation (including project evaluation) is a technique for making economic prescriptions - as for example, when a citizen has to vote on whether a wetland in her district should be drained to build a shopping mall. The idea is to evaluate an economy at a point in time before and after a hypothetical change (the policy change) has been made to it. In contrast, the literature on sustainable development arose because of a need to assess the performance of economies. Sustainability analysis involves evaluating economic change when the change involves the passage of time - as for example, when we ask, "how has the economy performed over the past thirty years?".

In Chapter 4 we studied evidence that the contemporary world is divided into rich and poor regions. It will no doubt have occurred to readers, though, that in identifying the various forms of capital assets in terms of which the poor are poor and the rich are rich, no mention was made of natural capital.

There was a reason for that neglect. It may seem obvious to say that our economies are built in and on Nature, but most contemporary accounts of economic possibilities facing Humanity don't include Nature as a capital asset. Nature doesn't feature in accounts of the macroeconomic history of nations because it doesn't appear in official publications of the vital statistics of nations. The extraction of minerals and fossil fuels is included (but not depreciated!) in modern national accounts, but with the exception of agricultural land, natural capital makes very little appearance. Nature's services appear in economics text books in passing, only to be side-stepped. That is how things are in the literature on the theory and empirics of long term economic growth and the economics of development.[11] The implicit assumption is that natural capital is of small importance in economic life because, as history shows, ideas, skills, and new forms of institutions can overcome Nature's scarcities. Prominent economists have claimed that Nature's services amount at best to 2-3% of GDP, the figure being the share of agriculture in the United States' national income.

The most serious problem with the stance adopted in development economics and the economics of growth is that it offers no contemporary empirical evidence for why it is safe to ignore Human-Nature interactions. Another problem is that it places an enormous burden on an experience in today's rich countries that is not much more than 250 years old. Extrapolation into the past is a sobering experience. Over the long haul of history (a 5,000 years stretch - say, upto about 1750 CE) economic growth even in the currently-rich regions was for the most part not much above zero (Maddison, 2001). Moreover, a close look at the experience of poor regions in South Asia and sub-Saharan Africa in contemporary times shows that increasing environmental scarcity combined with high population growth have had much to do with the persistence of poverty there (Dasgupta, 2003).

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[11] See, for example, standard textbooks on macro-economic growth and on economic development: Barro (1997), Ray (1998), Barro and Sala-i-Martin (2003), and Acemoglu (2009).

The economics of sustainable development is a response to the neglect of natural capital in models of economic growth. The subject developed as an attempt to bring Nature's services directly into economic reasoning. But the notion of sustainable development is not logically tied to the empirical fact that Nature is a factor of production. Whether a development path is sustainable is a reasonable question to ask in any world where capital assets are capable of depreciating, regardless of whether the assets comprise natural resources.

In their search for an index of sustainable development, scholars have explored a number of alternatives.[12] Summarizing an extensive literature, Parris and Kates (2003) distinguished two questions: (1) What is to be sustained? and (2) What is to be developed? Table 5.1 reproduces their list. If we were to make use of the distinction drawn in Chapter 4 between the determinants and constituents of well-being, we would notice that the column in Table 5.1 labelled "What is to be sustained?" for the most part consists of the determinants (nature; life support), while the column labelled "What is to be developed?" consists of a mixture of the determinants (wealth; productive sectors) and constituents (child survival; life expectancy; equity).

Parris and Kates used the classification in Table 5.1 to identify twelve ways in which scholars have variously defined "sustainable development". None offered an overarching notion of the object to be developed, nor did any offer a firm notion of the objects that are to be sustained. However, one proposal, put forward in World Commission (1987), has seemed so promising, that over the past two decades it has been subjected to extensive analyses by both ecologists and economists (e.g., Arrow et al., 2004).

5.5 Sustaining the Productive Base

To require that an object should be sustained over a period of time is to mean that it shouldn't diminish during that period. As sustainable development must refer to a path of development that sustains something, our first requirement is to state what that "something" should be. World Commission (1987: 70) defined sustainable development as "... development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Notice that the definition makes no mention of intergenerational well-being. Relatedly, it makes relatively weak demands on intergenerational justice. In the Commission's view, sustainable development requires that future generations have no less of the means to meet their needs than we do ourselves; it require nothing more. As needs are the austere component of human well-being, economic development could be sustainable in the Commissions's sense without having much to show for it. Notice also that the Commission's definition is directed at sustaining the determinants of well-being. In that view "sustainable development" requires that relative to their populations, each generation should bequeath to its successor at least as large an

[12] Pezzy (1992) was an early taxonomy. See also Pezzy and Toman (2002).

amount of the productive base as it had itself inherited from its predecessor. That raises another problem with the Commission reasoning. It leaves unexplained how the productive base should be measured.

Because economic development should be evaluated in terms of its contribution to intergenerational well-being, we define sustainable development as an economic path along which intergenerational well-being doesn't decline. The definition is built directly on the constituents of well-being. As the future is uncertain, intergenerational well-being is taken to include an ethically defendable attitude toward that uncertainty (Chapter 4*). Formally, we have

Definition 5.1. An economy follows a sustainable development path over a period of time if intergenerational well-being does not decline.

The problem with Definition 5.1 is that, as intergenerational well-being is a non-linear function of the flow of consumption over time (equations (4*.4)-(4*.5)), it is hard to use in empirical applications. The hope is to construct an index that (1) is linear in the quantities of goods and services, and (2) moves in the same way over time as intergenerational well-being. If such an index were found, it could be used as a surrogate for intergenerational well-being in Definition 5.1.

Today the most commonly used index of well-being is gross domestic product (GDP), so it is but natural to ask whether it could be that surrogate. GDP is the market value of the flow of final goods and services. In other words, GDP is a weighted sum of the flow of final goods and services, where the weights are market prices. As GDP is a linear index in quantities, it satisfies the first of the above requirements. Unfortunately, GDP isn't the surrogate we seek, because it doesn't satisfy the second requirement. One reason it doesn't satisfy it is that, as many ecological services are transacted in non-market institutions, official GDP doesn't record them. Another, more fundamental, reason is that GDP handles intergenerational concerns badly. (We confirm below that the United Nations' Human Development Index (HDI) suffers from that same weakness.) The rogue word in gross domestic product is "gross", meaning that GDP ignores the depreciation of capital assets. Among natural resources, that depreciation can range from a full 100% of the services drawn from oil and natural gas (the oil and natural gas that is burnt is unrecoverable, remember), to the degradation of ecosystems through mismanagment. It is therefore entirely possible that an economy enjoys growth in GDP over a period of time even while intergenerational well-being declines. As natural capital is especially vulnerable to overuse, serious criticisms of GDP appeared first in environmental and resource economics.[13]

[13] See Nordhaus and Tobin (1972), Mäler (1974), Dasgupta and Heal (1979), Hartwick (1990, 2000), and Lutz (1993), among others. Mäler (1991) and Weale (1997) provide outlines of a

As GDP is of no use, we look elsewhere. It is an interesting and important fact that there is a measure of an economy's productive base under which Definition 5.1 is equivalent to the World Commission's definition of sustainable development. That interpretation is an inclusive measure of "wealth". We demonstrate that below.

Even unguided intuition suggests that an economy's productive base consists of (a) the full range of capital assets to which it has access and (b) the myriad of both formal and informal institutions that influence the allocation, accumulation, and decumulation of those assets. By capital assets (henceforth, "assets"), we mean not only manufactured capital (roads, buildings, machinary and equipments), human capital (health, education, skills), population (size and demographic profile), and knowledge (science and technology), but also natural capital. Our notion of capital assets is an inclusive one.

It is useful to keep institutions separate from capital assets, even though scholars have been known to write about "institutional capital". By institutions we mean the arrangements that govern collective undertakings (the rule of law; social norms of behaviour; habitual social practices) - among which is the governance of markets, which themselves are institutions (Chapter 6). Being the totality of capital assets and institutions, the productive base consists of the determinants of intergenerational well-being.

The correct measure of an economy's productive base is the social worth of its stock of capital assets. We call that measure wealth. Proposition 5.1 (below) says that if wealth is defined in an inclusive way, it can replace "intergenerational well-being" in Definition 5.1 without changing the conception of sustainable development advanced there. In addition, wealth is a linear index of economic quantities. So it is the surrogate index we seek. Ecologists and economists have referred to the index as inclusive wealth (Arrow et al., 2004). We drop the adjective here because we take it for granted that an economy's wealth is estimated on the basis of the entire body of capital assets to which its members have access.

Institutions influence both current and future wealth in a number of ways that are formalised below. As illustration, imagine that because the State apparatus is corrupt, the judicial system is unreliable. Because people would find it difficult to protect their property rights, the value of their capital assets would be small. Institutions also influence the composition of consumption and saving; and they influence the character of future institutions. There are institutions that foster economic progress by having in place the structure of incentives that enable people to allocate capital assets in their most productive uses. But the latter can only happen if, in addition to the right incentives, people trust one another and have confidence in their institutions (Chapter 6). Well developed competitive markets and good governance together

complete system of national accounts inclusive of environmental natural resources. Lange, Hassan, and Hamilton (2003) and Perrings and Vincent (2003) contain applied studies on both valuation and resource accounts.

can combine to help create and maintain trust and confidence. They in turn promote economic efficiency and distributive justice. In contrast, there are institutions that are a hindrance. Under weak, misguided, or corrupt governance, goods and services end up in unproductive (even wrong) places. When vested interests govern economic decisions, neither efficiency nor equity gets much of a look-in. An economy's capacity to produce goods and services shrinks when its institutions deteriorate (owing to civil wars, ethnic strife, increased corruption) and its stock of other assets doesn't accumulate sufficiently to compensate for that deterioration. Likewise, the economy's capacity to produce goods and services shrinks when its stock of assets depreciates and its institutions aren't able to improve sufficiently to compensate for that depreciation. In Chapter 5* we show that it is possible to use macroeconomic data to quantify changes in the quality of institutions.

These arguments tell us that we should identify a capital asset not only in terms of its attributes, but also with regard to the person or persons who have access to it. That way we can admit distributional concerns in the study of human well-being. In what follows a lathe or a piece of information in the possession of (poor) person i will be taken to be a different asset from a lathe or a piece of that same information in the possession of (wealthy) person j. And so on.

Before we are able to develop the concept of wealth, we need to study a set of economic entities of great significance: shadow prices.

5.6 Shadow Prices

An asset's shadow price is its social worth (or scarcity value). Shadow prices are to be contrasted from market prices, to which they may bear little relationship (Section 5.3). Methods for estimating shadow prices are discussed in Chapter 5*. We begin with a rough and ready definition:

Definition 5.2. An asset's shadow price is the contribution a further unit of it would make to intergenerational well-being, other things being equal.[14]

Shadow prices provide the link between the constituents and determinants of intergenerational well-being. As in Chapter 4*, let $V(t)$ denote intergenerational well-being at t. $V(t)$ includes the well-being not only of people alive at t, but also the forecast at t of the well-beings of future people. But because the determinants of well-being are goods and services, we know in advance that simply to write V as a function of t (time) hides a lot of things. To confirm that it does, we return briefly to a deterministic world and consider once again the expression for $V(t)$ in equation (4*.4):

$$V(t) = U(C(t)) + U(C(t+1))/(1+\delta) + ...$$
$$= {}_t\Sigma^{\infty}[\Sigma U(C(s))/(1+\delta)^{(s-t)}]. \quad (5.1)$$

In what follows we use expression (5.1) simply to illustrate $V(t)$. The conceptual apparatus we

[14] A pollutant's shadow price would be negative.

construct below does not depend on V assuming that form. In expression (5.1) $C(s)$ is aggregate consumption at date s ($\geq t$) and δ is a non-negative constant. Recall our social evaluator, who was introduced in Chapter 4. $V(t)$ is constructed on the basis of the social evaluator's forecast (or prediction) of the flow of consumption at t and beyond. That forecast in turn is based on the economy's stock of assets at t, as well as the evolving structure of its technology, knowledge, people's preferences and aspirations, government policies, institutions, Mother Nature's choices, and all other factors that influence decisions and the consequences of those decisions. Similarly, the stock of assets at any date s in the future would be determined by the stocks at the previous date and the rest of the above factors. By proceeding from date to date, the entire future course of capital stocks and flows of investment and consumption could be determined. Thus the social evaluator's understanding of political economy enables him to forecast the future on the basis of the economy's capital assets at t. So, a forecast is not a guess, it involves an understanding of what the future would be if the economy's capital assets at t were other than what they happen to be. Reasoned forecasts are based on studying counter-factuals. And that requires an understanding of the evolving political economy.

5.6.1 Political Economy

Lipset (1959) famously observed that growth in income helps to promote democratic practice. The converse, that democratic practice and civil liberties promote material prosperity, had been suggested earlier, by Schumpeter (1942). An economy's institutions and its productive base co-evolve. Denote the evolving political economy by the symbol, ***M***. Formally, ***M*** is a (many-one) mapping from stocks of capital assets at any date to the entire future history of the economy from that date. We call ***M*** a resource allocation mechanism. In Chapter 5* we explain ***M*** more fully, and in Chapter 8 we construct formal models of socio-ecological systems to demonstrate the dynamics that characterise the accumulation and decumulation of capital assets. Here we merely note that the social evaluator makes his economic forecast at t on the basis of his reading of the economy's evolving political economy (***M***) and the capital stocks the economy has inherited at t. We make no particular assumption about the character of the economic regime. It could be that the State respects human rights and promotes justice. Or it could be that the State is inefficient, even predatory and corrupt. Our formulation accommodates all kinds of political regimes. Given ***M***, V at time t is therefore a function of the quantities of all capital assets at t.[15]

Assume there are H capital assets, denoted by the subscript h ($h = 1,2,...,H$). Recall that by capital assets we mean not only manufactured capital, human capital, population, and knowledge, but also natural capital. H is therefore a very large number. Let $K_h(t)$ be the quantity

[15] Economic theorists for the overwhelming part study the ***M*** under which $V(t)$ attains its maximum feasible value at each t. The optimum ***M*** (see Section 5.9) is a useful theoretical benchmark, but is of no use as the basis for empirical work.

M is taken to be time-autonomous here. We extend the account by studying non-autonomous systems in Chapter 5*.

of asset h at t, and let $\underline{K}(t)$ denote the vector of capital assets at t (i.e., $\underline{K}(t) = \{K_1(t),...,K_h(t),...,K_H(t)\}$). Then we have,

$$V(t) = V(\underline{K}(t),\boldsymbol{M}).^{16} \qquad (5.2)$$

We now revert to a world with risk and suppose that $V(\underline{K}(t),\boldsymbol{M})$ has built into it an ethically defendable attitude to the risks the economy faces beyond t. The simplest and most persuasive way to incorporate that attitude would be to regard $V(\underline{K}(t),\boldsymbol{M})$ to be the expected value of expression (5.1), where the expectation is taken over all the sample paths associated with $\underline{K}(t)$ and $\boldsymbol{M}$.[17] Let $P_h(t)$ be the shadow price of asset h at t. As with V, expressing shadow prices simply as functions of time is to mislead. Because V at t is a function of the entire future of the economy that has been predicted on the basis of the inherited vector of capital assets $\underline{K}(t)$, P_h at t is also a function of $\underline{K}(t)$ and that forecast. In short, $P_h(t) = P_h(\underline{K}(t),\boldsymbol{M})$.

Using equation (5.2), we may now re-state Definition 5.2 as

Definition 5.3. $P_h(\underline{K}(t),\boldsymbol{M}) = \partial V(\underline{K}(t),\boldsymbol{M})/\partial K_h(t), \qquad h = 1,2,...,H. \qquad (5.3)$

If h is a pollutant, $\partial V(\underline{K}(t),\boldsymbol{M})/\partial K_h(t) < 0$, meaning that $P_h(\underline{K}(t),\boldsymbol{M}) < 0$.

Shadow prices contain enormous quantities of information. Suppose, for example, the social evaluator's forecast is that business will be usual, and that under "business as usual" the economy will be depleting asset h (coral reefs, say) massively. Suppose there are goiod reasons for believing that there are no adequate substitutes in store. Unless future well-beings are discounted at a high rate (i.e., unless δ is large), $P_h(\underline{K}(t),\boldsymbol{M})$ would be large. Current shadow prices reflect future resource scarcities.

5.6.2 Uncertainty

Current shadow prices reflect future uncertainties as well. In recent years environmental scientists have uncovered any number of potential tipping elements in the Earth System (Chapter 8). However, locations of tipping points are uncertain. To illustrate, there is now a general consensus among experts that a rise in global mean temperature in excess of 2ºC above the current level could be catastrophic. The state of the Earth System (e.g., carbon concentration in the atmosphere) at which that threshold would be reached is, however, unknown. If the social evaluator is risk neutral, expected values of the relevant variables would suffice, and the shadow prices would reflect them. But as our social evaluator is risk averse (recall that U is strictly concave function of C (Chapter 4*)), shadow prices would reflect that aversion. The greater is the aversion to risk, the higher would be the absolute value of the shadow price of carbon in the atmosphere, other things being equal.

In order to construct a system of shadow prices, the social evaluator has to settle on a

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[16] That V is not an explicit function of t means that, as mentioned in the previous footnote, we are considering a (time) autonomous socio-ecological system. Chapter 5* extends the analysis to non-autonomous systems.

[17] Of course, the mapping $\boldsymbol{M}$ has to re-defined to include uncertain future events.

commodity that he takes to be the unit of account. Shadow prices of other goods and services are then expressed in terms of that commodity (e.g., "the price of a unit of wheat is 1.2 units of rice"). Economists call the commodity that has been chosen as the unit of account numeraire. In equation (5.3) *V* is numeraire. However, we could as well choose any one of the capital assets, say, $h = 1$, as numeraire. In that case we would divide each of the prices in equation (5.3) by $P_1(\underline{K}(t),\boldsymbol{M})$ to obtain a system of shadow prices in which the unit of account is the asset labelled $h = 1$. The set of equations (5.3) gives us a system of relative shadow prices. Absolute prices have no operational significance.[18]

In order to estimate an asset's shadow price, the social evaluator needs three pieces of information: (i) A descriptive model of the economy; (ii) the size and distribution of the economy's capital assets at the date the evaluation is undertaken; and (iii) a conception of intergenerational well-being. Taken together, requirements (i) and (ii) enable the social evaluator to arrive at a (reasoned) forecast of the economy. The pair of requirements are the basis for estimating the changes that would occur in the allocation of resources if an additional unit of the asset were made available free of charge (other things being equal of course). The reasoning involves counter-factuals. Requirement (iii) is the basis for placing a value on the changes occasioned by the additional unit of an asset. Based as they are on both "facts" and "values", shadow prices form the bridge between the constituents and determinants of human well-being.[19]

5.6.3 Subsititutes vs. Complements

Even without going into technicalities (for which see Chapter 5*), we can say a bit more about conditions (i) and (ii). At any date *t*, an asset's shadow price is a function of the stocks of all the economy's assets at *t* and on the entire future of the economy. But that's another of saying that shadow prices depend on both $\underline{K}(t)$ and $\boldsymbol{M}$. Future scarcities of natural capital are reflected in current shadow prices of goods and services. So, shadow prices depend also on the degree to which various assets are substitutable for one another, not only at *t*, but at all subsequent dates as well. Let us see how and why.

Growth economists frequently tell us that manufactured capital can substitute for natural capital (as in the case of double-glazed windows, that help to retain warmth and keep out noise). Shadow prices of substitutes are related in an interesting way. As a natural resource is depleted (say, because of excessive use), its shadow price increases, other things being equal. But the shadow prices of its substitutes also rise. That's because demand shifts to those substitutes. Shadow prices of substitute goods move together in the same direction.

Natural resources and manufactured capital assets are frequently not substitutes, but

[18] The point in question is similar to the choice of a currency unit. For example, prices could be expressed in dollars or cents. Nothing of significance would be affected by the choice.

[19] We note in passing that consumption discount rates (Chapter 4*) relate the shadow prices of current and future stocks of assets.

complements. To illustrate complements, consider "shoes". They are examples of (perfect) complements, in that if one of a pair is mislaid, the other becomes valueless. Natural capital and other forms of capital assets aren't quite like that, but they are often close enough. As a natural resource becomes scarcer (say, because of excessive use), its shadow price increases, other things being equal. The shadow prices of its complements, however, decline. To see why, consider that mangrove forests protect buildings and structures from storms and tsunamis (see Das and Vincent, 2009, for a recent empirical work on the subject). When a mangrove swamp is partially cleared (say, to make way for shrimp farms), its shadow price rises. But the shadow price of coastal buildings and structures declines, because they are now more vulnerable to Nature's forces.

To take an even more ominous example, consider that the shadow price of settlements in coastal areas will decline with further increases in atmospheric carbon concentration. That means the moderating influence of the carbon cycle on Earth's climate is complementary to the construction of buildings and structures in coastal areas. The shadow prices of (imperfect) complements move in opposite directions.

One can no doubt argue that barriers against storms and a rising sea level could substitute for mangroves. But the cost of those substitutes would prove prohibitive in poor, tropical countries. The general picture would seem to be that, with increasing populations and growing economic activity the pressure on ecosystems has over the decades become so great, that we are running out of substitutes. Vital ecosystems and manufactured capital are increasingly becoming complements of one another (MEA, 2003; Ehrlich and Goulder, 2007).

The language of shadow prices is essential if we wish to avoid making sombre pronouncements about sustainable development that amount to saying nothing. Most methods that are currently deployed to estimate shadow prices of ecosystem services are crude, but deploying them is a lot better than doing nothing to value them. That said, estimating shadow prices is a formidable problem. As both deep values (what value should we place on blue whales?) and deep facts (what would be the consequences of an increase in global mean temperature by 3°C?) are involved, we will never get shadow prices entirely "right". But that's not to say we would not be able to identify bands within which those shadow prices would be expected to lie. For example, the shadow price of a forest in the uplands of a watershed would include, among other things, the contribution it makes to the economic profitability of farmers downstream (reducing water runoff and siltation). Pattanayak (2004) and Pattanayak and Butry (2005) have arrived at rough estimates of the contribution Malaysian forests in the uplands make to downstream farmers' economic profits. They add upto some 5-10% of profits. Adding those figures to the value of forests based on the market value of the timber they harbour is a lot better than to rely exclusively on their market value.

There are cases where shadow prices can be approximated by market prices; but for most types of natural capital they differ greatly from market prices. Ecological economists have devised ingenious methods for estimating the shadow prices of various kinds of natural assets (Chapter 5*), but there is a long way to go before we have a reasonably complete set of shadow prices with which to estimate the wealth of nations. A systematic assault on such estimation exercises should now be a priority among national and international economic organizations.

Distortions in the pricing of primary factors of production in the market-place filter down to influence research and development. The latter in turn influences the character of technological change. Because Nature's services are underpriced in the market, innovators have little reason to economize on their use. We shouldn't be surprised when new technologies are rapacious in the use of natural capital.

5.7 Wealth and Well-Being

Assets are durable goods. Suppose an additional unit of a durable good is made available in an economy. Presumably, people there would enjoy an additional flow of goods and services over time. The durable good's shadow price is the capitalized value of that additional flow of benefits. We prove that in Chapter 5*. But here is an example by way of illustration:

Consider a hectare of agricultural land. If markets were competitive, the land's market price would be the present discounted value of the flow of profits that could be earned by cultivating it. If market prices of the inputs and outputs of agricultural production equal their respective shadow prices, the market price of the hectare would be its social value. Of course, the additional unit of a potentially productive asset could be so badly managed that its shadow price is negative. As noted previously, shadow prices depend not only on the asset's features, but also on the institutions governing the allocation of resources.

In the previous section we claimed that wealth is the correct welfare index. We now construct a proof.

An economy's wealth is the social worth of all the capital assets to which it's members have access, whether individually or collectively. Let t be the date at which wealth is estimated. Let $W(t)$ denote wealth at t. On using equation (5.3), we have

Definition 5.4. $W(t) = {}_h\Sigma P_h(\underline{K}(t),\boldsymbol{M})K_h(t)$. (5.4)

Definition (5.4) says that wealth at t is a function of $\underline{K}(t)$ and $\boldsymbol{M}$. So, we write $W(t) = W(\underline{K}(t),\boldsymbol{M})$.

Let Δ denote a small change in an economic variable. Δ is called a "perturbation". We are interested in two interpretations of Δ. Each leads to a distinct evaluation exercise.

(1) *Sustainability Analysis*. Δ is a brief passage of time. The latter is denoted as Δt.

(2) *Policy Analysis*. Δ is a small change in policy at a point in time. So Δ is a change in the political economy, $\boldsymbol{M}$, at a point in time.

Using equations (5.2)-(5.4), the equivalence we have ben claiming between intergenerational well-being and wealth can be expressed as follows:

$$\Delta V(\underline{K}(t),\boldsymbol{M}) \geq 0 \text{ \underline{if and only if} } {}_h\Sigma P_h(\underline{K}(t),\boldsymbol{M})\Delta K_h(t) \geq 0. \quad (5.5)$$

In words, (5.5) can be phrased as

Proposition 5.1. The perturbation Δ increases intergenerational well-being at t if, and only if, holding shadow prices constant at their values at t, it leads to an increase in wealth at t.

Proof: Equation (5.2) implies

$$\Delta V(t) = \Delta V(\underline{K}(t),\boldsymbol{M}) = {}_h\Sigma\{[\partial V(\underline{K}(t),\boldsymbol{M})/\partial K_h(t)]\Delta K_h(t)\}. \quad (5.6)$$

Now use equation (5.3) in equation (5.6). QED

Sustainability analysis is studied in the following section. Policy analysis is developed in Section 5.9.

5.8 Wealth Accumulation and Sustainable Development

In sustainability analysis, $\boldsymbol{M}$ is given. Let us apply Proposition 5.1 to sustainability analysis. For the purposes of illustration, suppose intergenerational well-being is the additive form (equation (5.1)). As will be clear, the analysis that follows does not depend on that particular specification of V. So as to keep the notation simple, let us suppose that time is a continuous variable.[20] Using equation (5.3), the continuous-time version of equation (5.1) reads as

$$V(t) = V(\underline{K}(t),\boldsymbol{M}) = {}_t\int^{\infty}[U(C(s))e^{-\delta(s-t)}]ds, \qquad \delta \geq 0. \quad (5.7)$$

5.8.1 Perturbations as Movement Through Time

In sustainability analysis $\Delta V(t)$ can be written as $[dV(t)/dt]\Delta t$. From equation (5.7) we have

$$\Delta V(t) = [dV(t)/dt]\Delta t = {}_h\Sigma\{[\partial V(\underline{K}(t),\boldsymbol{M})/\partial K_h(t)]dK_h(t)/dt\}\Delta t. \quad (5.8)$$

Dividing equation (5.8) by Δt, letting Δt tend to zero, and using equation (5.3), yields

$$dV(t)/dt = {}_h\Sigma[P(\underline{K}(t),\boldsymbol{M})]dK_h(t)/dt. \quad (5.9)$$

${}_h\Sigma[P(\underline{K}(t),\boldsymbol{M})]dK_h(t)/dt$ is the rate of change of wealth if that change is measured while holding shadow prices constant at their values at t. On using Definition 5.1 and equation (5.9), Proposition 5.1 becomes an empirically usable notion of sustainable development:

Proposition 5.2. An economy enjoys sustainable development at t if, and only if, holding shadow prices constant at their values at t, wealth is non-declining at t.

Proposition 5.2 can be re-phrased in more familiar terms. ${}_h\Sigma P_h(\underline{K}(t),\boldsymbol{M})dK_h(t)/dt$ is the social worth of the net change in the economy's stock of capital assets. But that's what economic accountants call net investment. So equation (5.9) and Proposition 5.2 can be restated as

Proposition 5.3. An economy enjoys sustainable development at t if, and only if, net investment at t is non-negative.

In Chapter 5* we generalize Propositions 5.2 and 5.3 so as to extend the applicability of the notion of sustainable development to an interval of time.

[20] We leave it to readers to construct the discrete time counterparts of the formulae that are derived below.

Propositions 5.2 and 5.3 are equivalence relationships. On their own they cannot tell us whether an economy is on a sustainable development path. What they do is to offer a method for determining whether it is doing so at a given point in time. Propositions 5.1-5.3 are very general. Other than the requirement that intergenerational well-being is a differentiable function of the economy's stocks of capital assets, they make no demand on empirics. It will also have been noticed that the proofs of the Propositions have not required any particular interpretation of intergenerational well-being. Expression (5.7) is merely illustrative of how we could conceptualize $V(t)$. The Propositions themselves do not demand that intergenerational well-being takes the form of expression (5.7). No matter what conception of intergenerational well-being is adopted by the social evaluator, there is a corresponding system of shadow prices for which Propositions 5.1-5.3 hold. In Chapter 5* we enquire briefly into the question whether differentiability of $V(K(t),\boldsymbol{M})$ is a demanding requirement. It will be argued that it is not at all demanding. We show there that V is differentiable almost everywhere even if the economy faces potential tipping points. Non-linearities in socio-ecological dynamics pose no problems for our analysis of sustainable development.

5.8.2 Commentary

Wealth is a weighted sum of an economy's stock of capital assets. An asset's shadow price serves as its weight. The weights are the rates at which assets substitute for one another in the measure of wealth. To illustrate, imagine that the economy "mislays" a unit of asset h at date t. Equation (5.4) says that wealth at t would not be affected if the economy were immediately given a gift of $P_h(\underline{K}(t),\boldsymbol{M})/P_{h+1}(\underline{K}(t),\boldsymbol{M})$ units of asset h+1 as compensation.

That wealth is a linear function of the stocks of capital assets is a huge advantage in empirical work. But there are scholars (e.g., Daly et al., 2007) who worry that the linear form hides an assumption, that knowledge and manufactured and human capital are always able to substitute for natural capital. Theirs is a misconception. Other than the requirement that V is a differentiable function, Propositions 5.1-5.3 are devoid of empirical content. The Propositions provide a tool for sustainablity analysis, nothing else. Proposition 5.2, for example, says that if the social evaluator wants to determine whether an economy is on a path of sustainable development, he should keep track of the economy's wealth, it says nothing more. The Proposition doesn't presume that capital assets can substitute for one another in production or consumption, nor that they are complements. Empirics enter via shadow prices. Imagine, for example, that asset h is a form of natural capital that is now close to a threshold level, crossing which would prove catastrophic to the economy. Suppose too that the exact point at which the threshold would be crossed is unknown. In such a case, if h+1 is a run-of-the-mill asset, $P_h(\underline{K}(t),\boldsymbol{M})/P_{h+1}(\underline{K}(t),\boldsymbol{M})$ would be a gigantic number. So large, perhaps, that it isn't possible to accumulate sufficient quantities of h+1 as compensation for any further decline in the stock of *h*.[21]

The matter can be explained another way. Equation (5.9) tells us that it is possible for an economy to accumulate manufactured capital, human capital, and knowledge, perhaps even improve the character of some of its institutions, but decumulate its natural capital to such an extent that its wealth declines. To illustrate with numbers, consider a closed economy, whose population and institutions remain unchanged over time. Suppose that in a particular year net investment in manufactured capital, human capital, and research and development, taken together, is 50 billion (international) dollars, estimated using shadow prices. For a small sized economy, that could look impressive. But if during that same year, its natural capital was to degrade and deplete by 60 billion dollars, wealth would decline by 10 billion dollars. The irony is that if natural capital doesn't enter national statistics, no one in the statistical office would realise that wealth had declined.

It can even be that despite the decline in wealth that year, GDP per capita shows an increase and the United Nations' Human Development Index (HDI) records an improvement. If that were to be so, students of the economy would be misled into thinking that all was well. One should note however that even though such a pattern of development can be viable for a while, perhaps even for a good many years, it wouldn't be viable indefinitely. If wealth were to decline continuously, the productive base would continually shrink. Eventually, GDP would have to decline, as would HDI. An economy can engineer GDP growth by "mining" its natural capital for an extended period of time, but eventually the scope for substitution will run out.

We have defined sustainable development at a point in time - say, a year. That's because national and international economic statistics usually are published on an annual basis. As is shown in Chapter 5*, Definition 5.2 can be extended to cover a period of time, even the indefinite future. There is no guarantee, though, that even if an economy's development path satisfies the sustainablity criterion today and has done so over the recent past, it will continue to do so in the future. It can be that GDP increases for a period of time, as does wealth. But if the latter grows by depleting natural capital, wealth will decline eventually, as will GDP.

Whether sustainable development is realizable in the future depends, among other things, on the scale of the economy. A rough and ready index of "scale" is the material component of GDP. If that becomes too large relative to the stocks of natural capital, the economy will be unable to maintain its wealth. Growth in the economy's scale will require that stocks of natural capital are drawn down so as to manufacture more material assets. If that happens (we should have said, "When that happens"!), what would be the structure of shadow prices? As an economy's scale increases, vital forms of natural capital (the atmosphere, the oceans) become scarcer, meaning that their shadow prices, relative to the prices of other forms of capital assets,

[21] The remarks here are adapted from Arrow et al. (2007), which was a reply to Daly et al. (2007).

grow larger and larger. But equation (5.3) says that when an asset's shadow price becomes very large, even a small further decline in the asset's stock would record a large negative figure for the corresponding term in net investment. That means net investment would be negative, unless the accumulation of other forms of capital assets was able to compensate. Of course, the extent to which the economy would be able to achieve substitution of manufactured and human capital assets for natural capital would depend on a number of factors, including the rate of technological progress. There can even come a point where no amount of investment in other forms of capital assets is able to offset further declines in vital forms of natural capital. Sustainable development would then be impossible, at least until further scientific and technological breakthroughs were to occur. It is impossible to imagine, though, what forms such breakthroughs could be if Earth's regulatory system was to be perturbed beyond recognition, such as, for example, a 5^0C increase in the mean global temperature.

All that brings us back, full circle, to the question whether knowledge can substitute for natural capital in production. That it has been able to do so in many cases in the past is no reason for thinking that it can do so indefinitely, and in every sphere of life.

5.9 Social Cost-Benefit Analysis: Further Discourse

Proposition 5.1 has been shown to be the basis for sustainability analysis. Remarkably, it is the basis for policy analysis as well. By a policy change we mean a change in the resource allocation mechanism, ***M***. Let Δ now be given its second interpretation. For concreteness, suppose the policy change is an investment project. The equivalence result in expression (5.5) says that the project should be accepted if an only if it raises wealth at the date it is started.

That may sound odd. How can wealth increase by the mere start of a project? As answer, recall that wealth is a stock, not a flow. A project typically requires investment now, with the promise of benefits at future dates in the form of higher consumption than would be available in its absence. It can be shown that the change in wealth occasioned by a project is the present discounted value of the flow of its social profits, net of investment costs. We prove this in Chapter 5*. Taking that finding as given for the moment, the equivalence relationship in expression (5.5) can be stated as

Proposition 5.4. An investment project, undertaken at t, increases intergenerational well-being at t if, and only if, its present discounted value (PDV) at t of the flow of social profits, net of investment costs, is positive.

In computing a project's PDV, what discount rates should the social evaluator use? Social rates, of course. If well-being is numeraire, δ would be the appropriate discount rate. If consumption is numeraire, the appropriate rate(s) would be consumption discount rates. Th dependence of the "social rate of discount" on the choice of numeraire was explained in Chapter 4*.

Investment projects are sometimes evaluated on the basis of their internal rates of return, the criterion being that a project should be accepted only if its internal rate of return (IRR) is no less than some acceptable figure. The criterion is defective. Suppose, as is customary practice, that consumption is numeraire. Suppose also that the consumption discount rate is constant over time. The criterion would be to accept a project if and only if its IRR exceeded the consumption discount rate. But as the evaluator knows the consumption discount rate, he may as well calculate the PDV of social profits. The internal rate of return of the project is superfluous.

A deeper problem with the internal rate of return arises in a world where the consumption discount rate is not constant. That is the normal situation because, as equation (4*.7) shows, the consumption discount rate is a constant only if consumption (per head) is constant. But if the consumption discount rate is not constant, the IRR criterion has no cutting power, unless it is larger than the consumption discount rate at all dates. Suppose the project's internal rate of return is not larger than the consumption discount rate during the project's lifetime. In that case there is no benchmark against which the social evaluator could judge whether the project is acceptable. We conclude that projects should be selected on the basis of the present discounted value of social profits. By Proposition 5.1 that is another way of saying that projects ought to be selected on the basis of their effect on wealth. The rule is simple to state: Accept a project if it raises wealth, reject it if it reduces wealth.

Social cost-benefit analysis is a powerful tool. Chichilnisky and Heal (1998) compared the costs of restoring the Catskill Watershed in New York State to the costs of building a water-purification plant costing 8 billion US dollars. The watershed's ecological function in the past had been, among other things, to purify water. The authors showed the overwhelming economic advantages of restoration over construction. Independent of the many other services the Catskill watershed provides, and ignoring the annual running costs of 300 million US dollars for a filtration plant, the capital costs alone showed a more than 6-fold advantage for investing in the ecosystem.

The Chichilniski-Heal study took the social objective (the supply of purified water to New York City) as given. They sought to identify the cost-effective way of realizing a given objective. Project evaluation, more generally, compares the costs with the benefits in order to determine whether a project should be accepted. That is hard work. Perhaps for that reason evaluation of ecological projects continues to be rare.

In a study of two afforestation projects in northern Nigeria, Andersen (1987) estimated the contributions shelter-belts and farm trees, respectively, make to household and farm productivity (by supplying building material, fuelwood, fruit, and fodder; and preserving soil and retaining moisture). The internal rate of return on investment in shelter-beds was found to be 15%; the corresponding figure for farm trees was 19%. It is hard to imagine that social discount rates would be anywhere as high as those figures. We should conclude that both were socially profitable projects. They would have raised wealth.

In another study on afforestation, Newcombe (1989) found that population pressure had led to rural deforestation in the regions of Debre Zeit and Debre Berhan, Ethiopia. Subsistence farmers had turned to dung as a source of household fuel. Newcombe showed that afforestation would enable farmers to switch to woodfuel as a source of household energy, releasing dung for use as fertilizer. The rates of return on such investment was estimated by him to in the astonishingly high range 35-70%.

In as yet unpublished work, Whittington et al. (2008) have evaluated alternative methods for supplying clean water to households. The authors observed that the traditional method in rich countries involves centralized water supply sources and wastewater treatment facilities, which have to combine with pipe networks for water distribution and sewage collection. The authors showed that this may not be the most cost effective method in poor countries. They did that first by evaluating a project in rural Africa that invests in deep boreholes with public hand-pumps. The benefits they considered included reductions in the incidence of diarrhea. At social discount rates of 3-6% a year, the project's profitability was found to be high (the benefit-cost ratio was approximately 3).

Whittington et al. (2008) also evaluated a community-led campaign in Bangladesh to steer localities from defecating in open grounds by constructing communal latrines. At social discount rates of 3-6%, the benefit-cost ratios of the programme were found to range from 2.4 to 7.5 depending on the sites chosen. The moral is important: in designing the supply of household water and sanitation facilities, the context matters.

5.10 Optimum Development

Good governance requires a continual search for policies that raise intergenerational well-being. In Chapter 4 that task was given over to our ubiquitous "social evaluator". In the previous section it was shown that social cost-benefit analysis provides the tool needed for identifying good policies. We now elaborate on the idea by showing how a repeated application of social cost-benefit analysis can enable the social evaluator to identify optimum policies, not just incremental improvements. The arguments that follow can be extended to allow for future uncertainties in economic possibilities. But for simplicity of exposition, we revert to the case where the economy is deterministic and the policy change in question is an investment project. We also assume, as is realistic, that time is discrete.

5.10.1 Local vs. Global Optimality

Let t be the date at which the project is being evaluated. Our account of the evaluation process is based on a thought experiment. We imagine that time can be frozen at t (the period may be a year, say) even while the social evaluator evaluates all projects that can feasibly be undertaken at t. That's a way of assuming that evaluation time is several orders of magnitude faster than real time.

The economy's inherited stock of assets is $\underline{K}(t)$. Imagine that the projects are small relative to the size of the economy. That means each of the Δs is small. Assume too that projects appear at the evaluator's desk on a sequential basis. At each step of the thought experiment the social evaluator makes use of the shadow prices that correspond to the $\underline{K}$ and $\boldsymbol{M}$ that prevail at that step. Because he knows Proposition 5.4, the social evaluator selects projects so long as they raise wealth ($W(t)$). That means he accept a project as long as the present discounted value (PDV) of the flow of social profits is positive. On each acceptance, however, the social evaluator's forecast of the future of the economy changes slightly, because acceptance means a small change in $\boldsymbol{M}$ and a small reshuffling of the vector $\underline{K}(t)$. Consequently, the system of shadow prices changes slightly. The social evaluator's search would be over once he discovers that there isn't a way to increase wealth any further at t. That point would be reached only when there is no feasible project left that yields a positive PDV of social profits, estimated at the shadow prices appropriate at that step in the evaluation process. We say that at that point the economy is at its optimum, meaning that the social evaluator would be unable to improve matters any further at t.

The above thought experiment describes an algorithm for identifying an optimum economic policy at t. The algorithm is known as the "hill-climbing method". It is the basis on which economic planning is formulated (Heal, 1973), and is also the basis on which evolutionary dynamics is modelled (Dawkins, 1996). But because the algorithm involves only incremental changes at each step, the optimum that is reachable is typically a local one, not the global one. Which of the potentially many local optima is reached depends on the capital allocation at the start of the algorithm, namely, the vector $\underline{K}(t)$.

Figure 5.1 depicts the problem. In order to depict it on paper, we have to imagine that there is a one-to-one mapping of the vector of capital stocks, $\underline{K}(t)$, into scalar numbers. Let the corresponding numerical index be $I(\underline{K}(t))$. So we express wealth as a function of the index as $W(I)$. Because socio-ecological systems are subject to non-linear dynamics, $W(I)$ typically has multiple peaks. Figure 5.1 portrays a case where $W(I)$ has two peaks, at I^{**} and I^*, respectively. $W(I^*)$ is a local optimum, whereas $W(I^{**})$ is the global optimum. $W(I_o)$ in contrast is a local minimum. The hill-climbing method would take the economy to I^{**} if the initial capital configuration at t happened to be to the left of I_o. Whether it was to the left of I_o would, however, be a fortuitous matter: the initial configuration would depend on the history of the economy prior to t. Should the initial configuration be to the right of I_o, the hill climbing method would take the economy to the local optimum I^*, which is less desirable than I^{**}.

The problem with the hill-climbing method is that it makes use only of local information, embedded as they are in the shadow prices. If the social evaluator inherited a capital configuration to the right of I_o and proceeded to climb the "hill" by choosing projects with the help of cost-benefit analysis, he would never know that I^{**} was available. Locating I^{**} (the global optimum) involves searching globally. Shadow prices are of little use in the global search.

Global search requires the evaluation of large projects. In order to do that though, the social evaluator has to estimate $U(C)$, which is a formidable task because $U(C)$ is a non-linear function. Once he is sanguine that $I(\underline{K}(t))$ is in the zone containing the global optimum (below I_o in Figure 5.1), he can proceed to evaluate small projects. If he were now to apply the hill-climbing method, he could expect to reach the global optimum.

5.10.2 Intertemporal Consistency of Optima

The optimum policy at t prescribes a mix of consumption and investments not only at t but also at all dates following t. Let us start at $t = 0$. The economy has inherited $\underline{K}(0)$. Imagine that the social evaluator has identified the optimum (whether global or local, it doesn't matter for the problem we analyse now). The optimum prescribes specific consumption levels for all $t \geq 0$, which we write as $C^*(t)$. The optimum also specifies the levels of the capital stocks to be attained at $t \geq 1$.[22] Denote the latter as $\underline{K}^*(t)$.

Comes the next date, $t = 1$. The economy has inherited $\underline{K}^*(1)$ in accordance with the previous date's optimum plan. Suppose the social evaluator seeks to maximize $V(1)$. He has access to $\underline{K}^*(1)$ as the vector of capital stocks. He evaluates projects just as he did in the previous period. Is the solution to the optimization problem at $t = 1$ the same as the one he identified at $t = 0$? In other words, would the social evaluator revise his recommendations or would he not need to make any changes? It is an interesting and important feature of expression (5.1) that if the social evaluator was to conduct the optimization exercise at $t = 1$, he would find that the optimum consumption plan for $t \geq 1$ remains $C^*(t)$, and that the optimum stocks of capital assets for $t \geq 2$ remain $K^*(t)$. In short, the economic policy he judged to be the optimum at $t = 0$ continues to be the optimum policy at $t = 1$.

That property of the optimum policy extends to all future dates. When intergenerational well-being takes the form given in expression (5.1), the ethical viewpoints at all dates are congruent with one another. Economists call that congruence intertemporal consistency.[23] Earlier we denoted a resource allocation mechanism by the symbol $\boldsymbol{M}$. Now let $\boldsymbol{M}^*$ denote the optimum resource allocation mechanism. Intertemporal consistency of the optimum implies that there will be no reason in the future to revise the policies that are selected today.

The concept of intertemporal consistency can be extended to a world facing future uncertainty. Optimum policies under uncertainty are contingent policies. They involve a specification of consumption and investment mixes under various contingencies. The

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[22] Recall that consumption is a flow, whereas the capital assets are stocks. Today's consumption can be chosen, but not the vector of capital assets.

[23] Rawls (1972) tried to build a theory of intergenerational justice solely on the requirement that the just policy be intertemporally consistent. But he did not specify the functional form of intergenerational well-being. Although a very great work, Rawls' theory of justice has nothing to say about justice across the generations. On this see Arrow (1973) and Dasgupta (1974).

consumption and investment decisions that are made for future dates are dependent on the natural events (e.g., the degree of precipitation; temperature) that will have occurred by then. A policy at t now reads: "... consumption at date s ($s > t$) should be $C^*(s,\theta)$ if θ happens to be the realization of natural events up to s, and ...", and so forth. But the rule that specifies what the consumption and investment mix is to be if and when a natural event occurs remains the same through time.

5.10.3 Optimum vs. Sustainable Development

If the social evaluator selects the optimum policy, intergenerational well-being at t would be

$$V(t) = V(\underline{K}^*(t),\boldsymbol{M}^*), \qquad \underline{K}^*(0) = \underline{K}(0). \qquad (5.10)$$

Write $V(\underline{K}^*(t),\boldsymbol{M}^*)$ as $V^*(t)$. Is $V^*(t)$ an increasing function of t? It can be shown that it is an increasing function (i.e. $V^*(t+1) > V^*(t)$) if δ is less than the productivities of the various forms of capital assets. So, optimum development satisfies the criterion for sustainable development. But it can also be shown (Dasgupta and Heal, 1979) that if δ is greater than those productivies, $V^*(t+1) < V^*(t)$ for all t, meaning that optimum development violates the sustainability criterion.

The result is intuitive. If δ is large relative to the productivities of capital assets, it is not worthwhile to increase wealth. As early well-being is greatly favoured in comparison to delayed well-being, it does not pay to invest in the future. Net investment is negative. The social evaluator's recommendation is that the economy should be wound down. Contrariwise, if δ is small relative to the productivities of capital assets, the optimum policy is to increase wealth. As early well-being is not favoured greatly in comparison to delayed well-being, it pays to invest in the future. Net investment is positive. The social evaluator's recommendation is that the economy should accumulate wealth.

In Chapter 4 it was shown that facts and values combine in interesting and sometimes unexpected ways to offer us social prescriptions. In Chapter 4* it was noted that δ is an important ethical parameter. Our present analysis gives us quantitative guidance on how to choose δ. If we value sustainable development, δ must not be chosen to be large relative to the other parameters that define the economy.

Our earlier suspicion is confirmed: optimum development is a different concept from sustainable development. A far sighted society would choose its ethical parameters with such care that the economic programme it judges to be optimum is also sustainable for all time. The idea of sustainable development is an aid to thinking ethically about the future.

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Table 6.1

Taxonomy of Sustainable Development Goals

What is to be Sustained	What is to be developed
Nature	People
Earth	Child survival
Biodiversity	Life expectancy
Ecosystems	Education
	Equity
	Equal opportunity
Life support	Economy
Ecosystem services	Wealth
Resources	Productive sectors
Environment	Consumption
Community	Society
Cultures	Institutions
Groups	Social capital
Places	States
	Regions

Source: Parris and Kates (2003), Table 1.

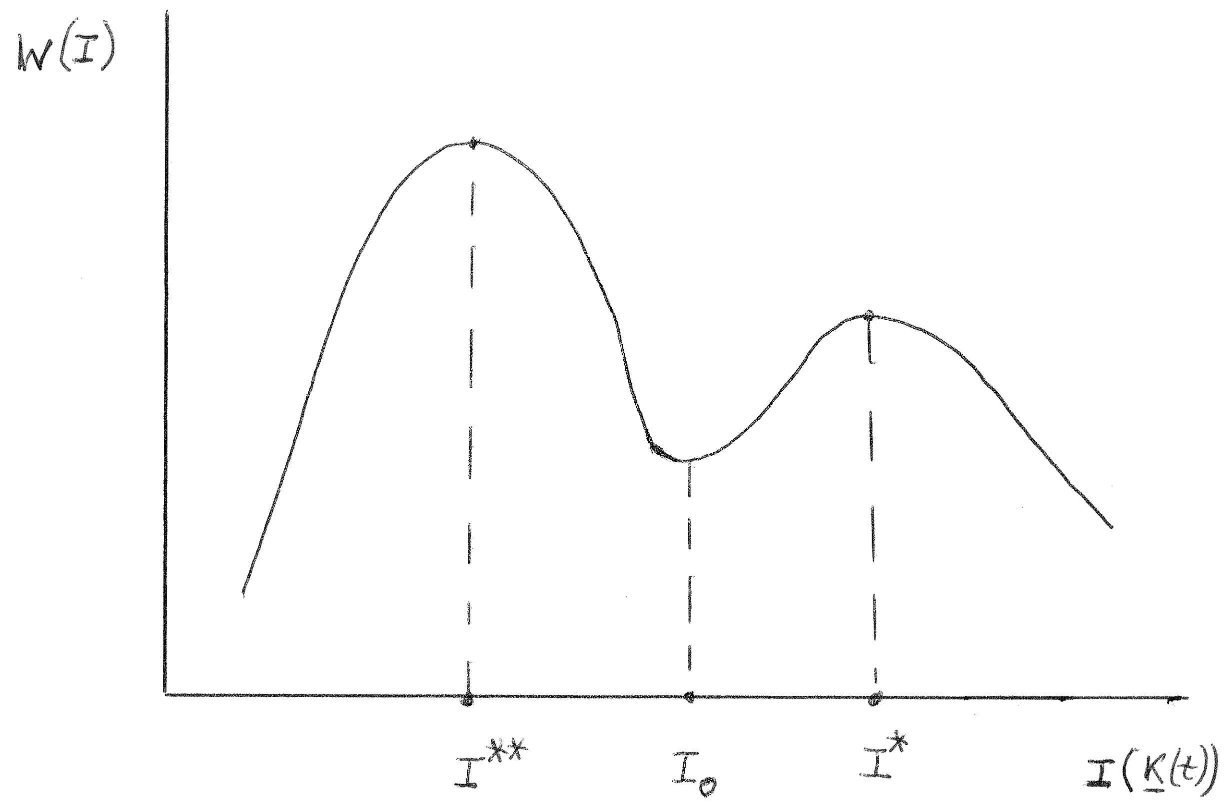

Figure 5.1