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VALUING THE FUTURE: ECONOMIC THEORY AND SUSTAINABILITY

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Valuing the Future: Economic Theory and Sustainability[1, 2]

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[1]This is the preface and first chapter of my book *Valuing the Future: Economic Theory and Sustainability*, published by Columbia University Press. The entire manuscript can be read online on the Columbia press web site, https://wwwc.cc.columbia.edu/sec/dlc/ciao/bookfrm.html. It can be purchased from the Press at www.columbia.edu/cu/cup/sales/index.html or from amazon.com at www.amazon.com.

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Preface

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Sustainability is a metaphor for some of the most perplexing and consequential issues facing humanity.Almost without exception, these issues are rooted in our economic behavior and organization. Yet it is not until very recently that there has been an economic theory of sustainability, or even any systematic application of existing theories to the issues to which it alludes. I hope that this book will help to place them more firmly on our research agenda, and will also suggest that economics can contribute to understanding sustainability and that thinking about sustainability can us help to understand economics. Scientific disciplines grow by interacting with problems that stretch them to their limits, and there are many such problems in the complex of environmental problems associated with sustainability.

One of the most intriguing of this set of problems is how we value the future, hence the title of this book. Economists have not really come to grips with valuing events that are centuries away. Typical economic time horizons differ by an order of magnitude from those that are typical for ecological or climatological phenomena. For economists, thirty years is a long time; for scientists concerned with the evolution of the environment, it is short. A lot of what follows is about reconciling these perspectives.

I develop a framework for thinking about some aspects of sustainability. The framework is one for modeling the dynamic interactions of economic and biological systems, studying the time paths that can emerge from these, and then selecting one of these as optimal. I investigate alternative approaches to optimality, inquiring whether there is a concept of optimality that captures the concerns that underlie the emerging interest in sustainability. I suggest that the essence of sustainability lies in three points: a treatment of the present and the future that places a positive value on the very long run, recognition of all the ways in which environmental assets or natural capital contribute to economic well-being, and recognition of the constraints on economic activity implied by the dynamics of environmental assets.

Embodying these concerns in a concept of optimality has important implications for patterns of optimal resource management over time, for the valuation of environmental assets, and for the way in which the use and the services of environmental assets are recorded in national income accounting.

Contents

Chapter 1

What is Sustainability?

> If a man takes no thought about what is distant, he will find sorrow near at hand. (Confucius)[1]

Can existing patterns of human activity safely and sensibly continue unaltered over the long term, or will such continuation lead to unacceptable consequences? This is the central issue underlying current discussions of sustainability.[2]

Some of the concerns prompting this question are by now a familiar part of the daily news agenda. Human consumption of carbon-based fuels, together with our depletion of carbon-consuming forests, is altering the natural carbon cycle of the planet, which since time immemorial has balanced carbon production by animals (humans included) against the consumption of carbon by plants and microorganisms and the sequestration of carbon in the oceans. The disturbance of this cycle is increasing the proportion of carbon dioxide in the earth's atmosphere, and there is now a consensus that this is slowly increasing the mean temperature of the planet. We do not understand fully the consequences of such a change: there seems to be a chance that for some regions of the world they could be apocalyptic and irreversible. Such observations lead one naturally to question whether current patterns of energy use can continue without eventually provoking unacceptable outcomes: in short, whether they are sustainable.

[1] Quoted in Newman [76].

[2] This definition, although far from those common in economics, is very close to that used by Holdren, Daily and Ehrlich [58], who say that "A sustainable process or condition is one that can be maintained indefinitely without progressive diminution of valued qualities inside or outside the system in which the process operates or the condition prevails".

Similar questions are prompted by the observed loss of biodiversity. According to distinguished biologists, we are driving species extinct at a rate unparalleled since the demise of the dinosaurs, more than fifty million years ago. These are irreversible, final losses; whatever our technological sophistication, we cannot re-create that which is extinct. The extinction is largely a result of habitat change, and also in some degree a consequence of pollution. Biodiversity is important in many different ways, so again the question arises: are the dimensions of human activity leading to biodiversity loss sustainable? Or will they impoverish us?

A key point is that it is economic forces, economic decisions, that are driving phenomena such as global warming and biodiversity loss. The decision to use fossil rather than solar energy is an economic decision; the decision to use more rather than less energy is also an economic decision. The changes in habitat which lead to extinction are again economically driven; it appears to be more profitable to chop down rainforests and plant coffee or other cash crops than to leave them intact. The choice of polluting rather than nonpolluting technologies is another economic choice. So behind many of the offending dimensions of human activity are economic choices and economic calculations. We will not significantly change the potentially unsustainable aspects of human activity unless we can develop an economic environment within which they are no longer attractive. In other words, we need to change the rules of the economic game so that it becomes economically rational to pursue sustainable alternatives. A good economic system harnesses private interests in the public good, so that as Adam Smith noted[3]:

> Every individual . . . neither intends to promote the public interest, nor knows how much he is promoting it. He intends only his own security, his own gain. And he is in this led by an invisible hand to promote an end which was no part of his intention. By pursuing his own interest he frequently promotes that of society more effectively than when he really intends to promote it.

How could this work? Economic decisions are guided by prices: prices fix the costs of alternative ways of doing business, and the returns from business opportunities. So the phrase the rules of the economic game refers to the ways in which prices are determined. We need prices that reflect better

[3] [93], book 4, chapter 2, first page.

the costs associated with nonsustainable policies. This is not a new observation: a long tradition of environmental economics emphasizes the differences between the private and social costs of environmentally harmful activities, and the need to devise economic institutions to close that gap. In a general sense this book is a contribution to that tradition. We have already made progress in that direction, through institutions such as tradable emission quotas and pollution taxes.

There are however several dimensions in which the issue of sustainability is different from, and more demanding than, the earlier issues raised by environmental economics. One is the time dimension. Sustainability is above all about what happens in the long term: about whether we can continue "forever" as we are, and whether the economic rules of the game lead us to make choices that are viable in the long term. Here *the long term* denotes a period much longer than that normally considered in economic analyses, typically at least half a century and sometimes as long as several centuries. These time periods pose a particular challenge for the economists' traditional practice of discounting, and an aim of this book is to consider the alternatives.

A second dimension in which the current concern with sustainability is particularly challenging, is that it requires us to address the interactions between our economic systems and a wide range of natural ecosystems. We are coming to realize, in part through the process of losing them, that environmental assets are key determinants of the quality of life in most societies. These assets—forests, clean water, clean air, species, rivers, seas, and many more—are not like physical or financial assets: they are alive and have dynamics, requirements, imperatives of their own. Recognizing this and recognizing that they provide the essential infrastructure for human existence is a key step on the road to building an economic framework that can contribute to the development of sustainable policies. In modeling this framework, one has to draw on the recent literature on ecosystem services and their role in sustaining human societies: the volume edited by Daily [33] is a key contribution here.[4]

My aim here is to review the existing conceptual economic literature on sustainability, and then to develop the concept further within the context of models of the optimal dynamic management of an economy endowed with natural resources. I will use this to suggest that we can give a clear analytical content to the idea of sustainability and can build on this to establish frameworks for project evaluation, shadow pricing, and environmen-

[4] See also the book by Baskin [9].

tal accounting, all of which are consistent with the underlying theoretical framework, in precisely the same way that current approaches to project evaluation and national income accounting are consistent with and draw their intellectual justification from the discounted utilitarian approach to optimal growth theory.[5] In the next section I review the existing literature on sustainability, and I also review certain existing concepts that, although not explicitly linked to sustainability, can contribute to the formalization of this concept. Prominent among these are the Fisher-Lindahl-Hicks concept of income as the maximum that we can consume without reducing our wealth and the Meade-Phelps-Robinson concept of the golden rule of economic growth as the configuration of the economy leading to the highest permanently maintainable consumption level.

It is not my intent here to cover all possible interpretations of sustainability or all aspects of a theory of sustainability. My goal is to develop a framework for analyzing sustainability in the context of economic dynamics and of the design and management of economic development strategies. I use a deterministic framework, one that is highly aggregated and simplified, an extension of Solow's classic growth model [94] as modified by Dasgupta and Heal [36]. Though simple, this model has been found by many researchers to yield interesting and robust insights, and the same proves to be true in the present context.

My agenda does not address many aspects of sustainability, some of them unquestionably very important. But one has to start somewhere. Aspects that are central but omitted are those stemming from uncertainty,[6] technical change, and the need to manage the use of global commons or public goods such as the atmosphere and the oceans. Over long time horizons, which are central to discussions of sustainability, uncertainty is pervasive: what will the world look like one century ahead? Two centuries? Technical change is one of the main sources of this uncertainty: in principle, technical change could render many currently threatening practices benign or unnecessary. Economists have often modeled technical change by an assumption of exponentially rising productivity. However, the current problem seems

[5] I am referring to the fact that most of the current practice of cost-benefit analysis has its origins in the works of Dasgupta Marglin and Sen [41] and of Little and Mirrlees [69], who took the relatively abstract ideas of the theory of optimal economic growth and applied these to an analysis of the rules governing the use of shadow prices for project evaluation.

[6] See the paper by Asheim and BRekke [8] and the volume by Chichilnisky, Heal, and Vercelli [29], and in particular Beltratti, Chichilnisky and Heal [13]. See also Chichilnisky and Heal [25] for a non-technical overview.

altogether too important to use such a naive approach: any constraint can be avoided in the long run on such a scenario. And although there are models of endogenously generated technical change, we actually know very little about the factors generating enhanced productivity. A satisfactory treatment of these topics will have to wait, but in the meantime there are aspects of sustainability on which we can make progress.

In the management of the global commons, a key issue is the assignment of property rights in and management of the use of global public goods such as the atmosphere, the oceans, and reserves of biodiversity. Many complex and interesting economic issues arise when one considers how best to manage these. Of course, they are public goods, so we have to be concerned about the possibility of "free riding": they are a very particular type of public goods, namely privately produced public goods. They are privately produced in that the amounts of carbon dioxide or chlorofluorocarbons in the atmosphere are the results of large numbers of decisions made by individuals and firms about lifestyles, technologies, and so on. This introduces an element into the attainment of efficient allocations that is absent from conventional public goods such as defense or law and order, and has interesting implications for the use of tradable permits, a method of establishing property rights and harnessing market forces in the service of the environment that is rapidly gaining attention. In particular, it implies that the initial distribution of property rights among participants in the permit market determines whether the equilibrium attained by the market after trading will be Pareto efficient. These issues are studied in detail in Chichilnisky and Heal [26] and Chichilnisky Heal and Starrett [28].

1.1 History of Sustainability

Only recently has sustainability become an influential and widely used word. At the 1992 Earth Summit in Rio, considerable attention was devoted to sustainability, and the concept is embodied in the resulting UN Framework Convention on Sustainable Development. In addition, the Organization for Economic Cooperation and Development, the United Nations Committee on Trade and Development, the U.S. Presidential Council on Sustainable Development, and many other domestic and international policy-oriented institutions are devoting time and energy to the analysis of sustainable policies. An environmentalist might find this encouraging. An economic theorist or a public policy economist, on the other hand, could easily find this very worrying, for sustainability is not part of our lexicon; it has no established economic meaning. There is a literature on sustainable development, but this is recent and partial at best, and one certainly could not say that it represents an economic consensus on how to formalize and make operational the ideas associated with sustainability. The concepts and concerns that underlie sustainability are not new. Certainly they go back at least to the 1970s; the Bariloche model (Hererra et all [56], Chichilnisky [17]) emphasized relevant issues in 1976:

> . . underdeveloped countries cannot advance by retracing the steps of . . the developed countries . . it would imply repeating those errors that have lead to . . deterioration of the environment . . The solution . . must be based on the creation of a society intrinsically compatible with its environment. ([17], p. 24)

The concept of “a society intrinsically compatible with its environment” is central: the goal of the literature on sustainability is to understand what this might be and how to implement it. This same model also introduced the concept of “basic needs” as a way of formalizing the minimum requirements needed for successful participation in society and linked the satisfaction of these basic needs with “the creation of a society intrinsically compatible with its environment.” Around the same time, the United Nations Conference on the Human Environment in Stockholm (1972) coined the phrase *sustainable development*, and the United Nations Environment Program was founded.

More recently, the Brundtland report [101] produced the following widely-quoted remark: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” The timeliness of this report, and the ease with which this phrase rolls off one’s tongue, has something to do with the attention given to the concept in recent years. However this ease is a little misleading: there is no corresponding ease of intellectual assimilation.

Two key concerns are expressed in Bariloche and Brundtland: recognition of the long-run impact of resource and environmental constraints on patterns of development and consumption, and a concern for the well-being of future generations, particularly as this is affected by their access to natural resources and environmental goods. These are an alternative way of articulating the concern that started this chapter, namely whether existing patterns of human activity can safely and sensibly continue unaltered over the long term, or whether such continuation will lead to unacceptable consequences.

The framework I develop in the following chapters addresses both of these concerns, which seem very well founded and deserving of explicit recognition and analysis.

1.2 Possible Formalizations

While laying the foundations for modern microeconomics, Hicks [57] defined income as "the maximum amount that could be spent without reducing real consumption in the future." A similar definition can be found earlier in the works of Lindahl [68] and even earlier in those of Fisher [44].[7] Clearly there is a concept of sustainability here: income is defined as sustainable consumption. This has points of contact with the Brundtland report's concern for meeting the needs of the present without compromising the ability of future generations to meet their own needs. It appears that Brundtland may be saying no more than that we, the present, should consume within our income. However, for this to be true, our concept of income would have to be a sophisticated one indeed, encompassing income of all types, psychic as well as monetary, from environmental assets, and adjusting monetary income to allow for the depletion of environmental assets.

This observation naturally raises the question of the appropriate measure of national income and the closely related issue of green accounting. This phrase refers to national income accounting conventions that reflect adequately the services provided by environmental assets and that capture as a cost to society the depletion of natural resources. Developing a satisfactory set of conventions in this area is intimately linked to provision of a satisfactory definition of sustainability: in fact, as we shall see later, the former is the mathematical dual of the latter.[8] A review of the work to date in this field is in Dasgupta, Kriström, and Mäler [40].[9] The interpretations of the Brundtland report's concept of sustainability as consuming within society's income, broadly and greenly defined, should immediately alert us to a possible limitation. Although in general and on average it makes sense to consume within one's income, there are times at which one chooses to consume significantly less in order to consume more at other times. Consuming precisely our income would never allow us to save or dis-save: it would freeze us where we are. Those familiar with the Rawlsian definition

[7] Nordhaus [78] reviews Fisher's concept of income in the context of sustainability. I occasionally refer to this concept of income as Hicksian, as I believe that this is the way in which it is widely recognized, even though its intellectual origins seem to predate Hicks' use of this framework.

[8] *Duality* here is used in the sense of functional analysis: the dual of a space is the set of all real-valued continuous linear functions defined on it.

[9] See also Asheim [5].

of intertemporal justice (see below) will see some semblance here.

The Fisher-Lindahl-Hicks definition of income is often paraphrased as "the maximum consumption that maintains capital intact." In the context of this paraphrase of Hicks, it is natural to mention recent work by Daley [34] and Pearce, Markandya and Barbier [80], in which they argued for maintaining intact *natural* capital stocks as a condition for sustainability. Sustainable paths for them are paths that maintain intact, in some sense, our stock of environmental assets.

Solow and Hartwick (see Solow [96] and Hartwick [50]) generalized this in the direction of the Fisher-Lindahl-Hicks concept of income and argued that sustainability is captured by a Rawlsian definition of intertemporal welfare[10]: from a Rawlsian perspective, welfare is maximized by maximizing the welfare of the least well-off generation. One can write this formally and succinctly as

$$\max_{\text{feasible paths}} \left\{ \min_{\text{generations t}} \{\text{Welfare}_t\} \right\} \tag{1.1}$$

where Welfare_t denotes the welfare level of generation t, so that we are required by the definition of intertemporal justice in (1.1) to do two things: for any feasible path to find the welfare level of the least well-off generation on that path and then to seek the feasible path amongst all feasible paths that gives the greatest value of this minimal level.

An interesting result by Hartwick and extended by Dixit, Hammond and Hoel [42], and Solow, shows (unfortunately under fairly strong assumptions) that if a country invests an amount equal in value to the market value of its use of exhaustible resources, then it solves the Rawlsian problem (1.1) and achieves the highest possible level of utility for the least well-off generation. Remarkably, it also achieves the highest feasible constant level of utility given the economy's initial stocks of capital and resources. Investing an amount equal in value to the market value of the use of exhaustible resources is, of course, maintaining intact the value of all capital stocks, including natural capital stocks. In other words, it is living within our Fisher-Lindahl-Hicks income, and a generalization of the Daley-Pearce concept, generalized to allow for the substitution of natural by produced capital of equal market value. As my colleague Graciela Chichilnisky observed,[11]

[10] The reference here is to John Rawls' "A Theory of Justice" [82], in which Rawls defined a just society as one so organized as to promote to the greatest extent the well-being of the least well-off group. By analogy, a Rawlsian definition of justice between generations is the program of economic evolution that maximizes the well-being of the least well-off generation.

[11] Private communication.

although this result is fascinating and surprising, it is also slightly suspect from an environmental perspective: imagine all trees replaced by buildings of equivalent value. This maintains the total value of capital stocks intact, yet it is clear that this is not what we mean by sustainable development! Perhaps supply and demand would take care of this problem: as we approach such a situation, the price of trees might rise, and that of dwellings fall, to a point where it is impossible to replace trees by dwellings of equal market value. Such an outcome requires a property such as Walrasian stability of the economy's equilibrium[12]: known sufficient conditions for this are very restrictive.[13] This problem is related to a shortcoming in the existing formalizations of the Rawlsian approach: they value natural resources only as inputs to production, not as assets of value in their own rights. For this reason, these approaches can lead to solutions in which all or most natural capital is replaced by produced capital. I argue below that we have to recognize explicitly all the values of environmental assets, and not just value them as inputs to the productive process.

In the 1960s, Meade [74], Phelps [81] and Robinson [86] introduced the concept of the golden rule of economic growth, which was defined as the configuration of the economy giving "the highest indefinitely maintainable level of consumption per capita." In the standard one-sector neoclassical growth model—the Solow model—this configuration is characterized by equality of

[12] An economy displays Walrasian stability if the process of prices adjusting proportionally to the difference between demand and supply leads to an equilibrium at which all markets clear. Formally, consider the process $dp/dt = D(p) - S(p)$ where p is a vector of goods prices and $D(p)$ and $S(p)$ are respectively vectors of demands and supplies at the price vector p. Walrasian stability implies that this process has a stable equilibrium at which $D(p) = S(p)$. Few economies seem to satisfy this condition: for more details see Arrow and Hahn [2].

[13] For further development of this point, see Chichilnisky [21].

the rate of return on capital to the rate of population growth[14]:

Rate of return = Population growth rate

The definition of the golden rule as giving the highest indefinitely maintainable level of consumption per capita is clearly another statement about sustainability, but made in a framework devoid of any environmental and resource constraints. The golden rule describes the configuration of the economy giving the highest sustainable utility level.[15] It is natural to extend this concept to dynamic economic models incorporating environmental constraints, and in the following chapters I develop and analyze such an extension, the green golden rule introduced in Beltratti, Chichilnisky and Heal [10][11][12].

Note a subtle but very important distinction: finding the configuration of the economy that gives the highest indefinitely maintainable level of consumption per capita is *not* the same as achieving the highest constant level feasible from specific initial stocks of capital and resources. The requirement that a utility level be immediately attainable from the economy's initial conditions is restrictive, and in general rules out the golden rule path or the green golden rule path. This best constant utility path attainable from the initial conditions of the economy,[16] according to Dixit, Hammond, and Hoel, Hartwick, and Solow, is the outcome of investing in produced capital so as to maintain intact the total value of natural and produced capital. This is maximization subject to specific initial conditions: the golden rule is the selection of the configuration that maximizes over all maintainable configurations, independently of initial conditions. Under certain conditions, paths that are optimal in various senses are asymptotic to this configuration.

[14] For those familiar with growth theory, the derivation is simple. Let $C + I = F(K, L)$ where C denotes total consumption, I total investment, assumed to be given by $sF(K, L)$, where K is the total stock of capital and L the labor force. F is the aggregate production function, assumed to show constant returns to scale. Letting $k = K/L$, the rate of population growth be λ and $f(k) = F(K, L)/L$, we have

$d \ln K/dt - d \ln Ldt = dk/dt = sf(k)/k - \lambda$.

Hence $dk/dt = 0$ i.f.f. $sf(k) = \lambda k$. But $C/L = c = (1 - s) f(k) = f(k) - \lambda k$. Hence over paths on which $dk/dt = 0$, c is maximized when $df/dk = \lambda$. The highest indefinitely maintainable level of consumption is attained when the return to investment equals the population growth rate. Note that this level will generally not be immediately attainable from any initial conditions: $df/dk = \lambda$ requires a particular level of capital per head, which may exceed that at the economy's initial conditions.

[15] Actually it describes the configuration giving the highest sustainable consumption level, but as in these models utility depends only on consumption and is increasing in consumption, this is the same as seeking the highest sustainable consumption level.

[16] Under certain specific assumptions about the technology.

It emerges from this very brief review that there are clearly elements of formal frameworks that have been available to us for a quarter of a century or more and seem to capture some aspects of what we mean by sustainability. The Fisher-Lindahl-Hicks definition of income and the golden rule are foremost among them. But none of them seem to address fully the concerns articulated in the quotes above from the Bariloche model or the Brundtland report.

1.3 Limitations of Earlier Approaches

Consider each of the approaches just listed. They all have limitations. The Rawlsian approach ties us to the historical accident of initial conditions (see Solow [95] or Dasgupta and Heal [37]): if, as is typically the case in developing countries, the present generation is also the poorest, seeking to maximize the welfare of the least well-off generation does not legitimize a policy of saving now for the future, however great the future returns. The point is that such saving would involve a transfer from the poor present to the presumably richer future, which cannot be sanctioned by a Rawlsian view of justice, oriented as it is solely to the position of the poorest. Yet such saving and capital accumulation is for many the essence of economic development.

As we shall see in detail below, the golden rule does just the opposite of Rawls: it implicitly defines a criterion that disregards the present totally provided we get the long run right, in the sense of attaining the greatest possible maintainable utility level. It could justify a very Stalinist[17] approach to economic development. However I suggest its use in combination with other elements, in an approach proposed by Chichilnisky [20]. This interesting approach is studied in detail in chapter 5, and its implications developed at length in subsequent chapters.

Stationarity of natural capital as a criterion, as suggested by Daley and Pearce, has the merit of preserving natural assets. Otherwise it seems arbitrary and places undue emphasis on the status quo, although it does avoid scenarios under which all natural capital is replaced by produced capital of equal value. But given ecological thinking about resilience and spontaneous change in natural systems (see for example Hollings [59]), stationarity seems inappropriate to characterize sustainability. It appears that in the biological world, stillness describes death, not life! Perhaps more important, although the Daley-Pearce approach has the presumably desirable effect of ensuring

[17] The term is Bob Solow's.

environmental preservation, it does this by fiat, rather than as a consequence of any deeper general principles. This makes it inflexible, and impossible to use for exploration of the many complex trade-offs that are at the center of economic policy formulation. Indeed, an inability to pose and explore trade-offs is a shortcoming of all of three approaches mentioned here (the Rawlsian, that of Daley and Pearce, and that based on the golden rule). The great merit of discounted utilitarianism, the approach to which we turn next, is that it is flexible enough to allow many trade-offs to be posed and investigated. If, as seems to be the case, we are uncertain of the values which we want to express in our evaluation of environmental projects, this flexibility has great attraction.

1.4 Discounted Utilitarianism

The default criterion for ranking development paths and investment projects, including environmental conservation projects, is provided by the discounted utilitarian framework. Following the approach introduced by Bentham in the nineteenth century, the best path is said to be that which provides the greatest present discounted value of net benefits. Many authors have expressed reservations about the balance that this strikes between present and future. Cline [31] and Broome [16] argued for the use of a zero discount rate in the context of global warming, and Ramsey and Harrod, the founders of the modern theories of dynamic economics, were scathing about the ethical dimensions of discounting in a more general context, commenting respectively that discounting "is ethically indefensible and arises merely from the weakness of the imagination" and that it is a "polite expression for rapacity and the conquest of reason by passion" (see Ramsey [83] p. 543, Harrod [49] p. 40 and also Heal [55]).[18] It is ironic that a practice so roundly condemned by the founders of intertemporal economics has come to occupy so central a position in the field. It may be fair to say that until now discounted utilitarianism has dominated our approach more for lack of convincing alternatives than because of the conviction it inspires. It has proven particularly controversial with non-economists concerned with environmental valuations.

The legitimacy of discounting is a complex issue, and the comments of Ramsey and Harrod, though perceptive and pointed, do not do it justice. As we shall see in chapter 5 (see also Heal [54]), discounting of future utilities is in some sense logically necessary; without it one encounters a variety of

[18] Heal [55] argued that a zero consumption discount rate can be consistent with a positive utility discount rate in the context of environmental projects.

unsettling paradoxes. The distinction between discounting future utilities in the evaluation of development programs and the discounting of future benefits in cost-benefit studies has also to be borne in mind (Heal [55]). Discounting future utilities does not necessarily imply that it is appropriate to discount future benefits in cost-benefit studies.

A positive utility discount rate forces a fundamental asymmetry between the treatments of, and the implicit valuations of, present and future generations, particularly those very far into the future. This asymmetry is troubling when dealing with environmental matters such as climate change, species extinction, and disposal of nuclear waste, as many of the consequence of these may be felt only in the very long run, a hundred or more years into the future. At any positive discount rate these consequences will clearly not loom large (or even loom at all) in project evaluations. To illustrate, if one discounts present world GNP over two hundred years at 5% per annum, it is worth only a few hundred thousand dollars, the price of a good apartment. Discounted at 10%, it is equivalent to a used car.[19] On the basis of such valuations, it is irrational to be concerned about global warming, nuclear waste, species extinction, and other long-run phenomena: the long-run future is irrelevant! Yet societies obviously *are* worried about these issues, and are actively considering devoting very substantial resources to them, as noted in the opening section of this chapter. So a very real part of our concern about the future is clearly not captured by discounted utilitarianism. Because economic institutions and procedures should capture society's values and concerns, we have to find a more satisfactory alternative. There is interesting empirical evidence (see Lowenstein and Thaler [72]), to which we return in chapter 5, that individuals making their own decisions do not compare present and future by discounting the future relative to the present at a constant discount rate, as is standard in the discounted utilitarian approach. Rather, they seem to apply a discount rate that varies with the time horizon, and is quite high over short periods (15-20% over a few years), but falls rapidly with the length of the horizon under consideration, being as low as 2% for horizons of several decades.

We need a framework for considering very long time horizons that is sensitive to both present and future, and possibly more consistent with the approach implicit in individual choices. This in part is driving an interest in formalizing the concept of sustainability, and the associated unease with the hitherto standard economic framework based on discounted utilitarianism.

[19] These are at New York prices.

1.5 Sustainability: a Preliminary Definition

We have now outlined earlier approaches to sustainability, the intuitions and concerns behind this concept, and the limitations of earlier approaches. The time has come to build on this. I suggest here, and argue in detail below, that the essence of sustainability lies in three axioms:

- A treatment of the present and the future that places a positive value on the very long run
- Recognition of all the ways in which environmental assets contribute to economic well-being
- Recognition of the constraints implied by the dynamics of environmental assets.

The first of these points is captured in an interesting definition of sustainability proposed by Chichilnisky [20], and also by the green golden rule and the overtaking criterion with a zero discount rate. The second point relates to the way in which we value environmental assets. It implies that we recognize all the dimensions of their value.

1.6 Valuing Environmental Assets

Finding a framework that allows for a complete integration of the ways in which environmental assets contribute to the economy is a central part of the research agenda. Unfortunately systematic research has only begun to scratch the surface of this complex and far-reaching issue. However, it has already shown that there are myriad ways in which environmental assets are sources of value.[20]

Environmental assets are valuable as sources of knowledge; this is one of the sources of value in biodiversity, the source that is tapped in biological prospecting and in the famous Merck-InBio deal.[21] The point here is that many pharmaceutically valuable products and many agriculturally valuable crop strains have been developed from species found in the wild. This point cannot be overemphasized: according to a report to the National Academy of Sciences of the United States, one third by value of the pharmaceuticals sold in the United States, over $60 billion in current market value, were

[20] The most comprehensive compilation of the values of environmental assets is in Daily [33]. For a review of some of the underlying biology, see Baskin [9].

[21] For details of this and similar deals, see Chichilnisky [19].

originally obtained from plants or insects, and many of the more robust grain species have likewise been derived from specimens found in the wild. Obtaining pharmaceutically valuable products from plants, insects, or animals, largely from those in rainforests, is now recognized by most major drug companies as a commercially valuable strategy, as is the systematic study of traditional healing methods, which sometimes give clues to pharmacologically active compounds. A significant number of pharmaceutical companies now actively investigate the medical efficacy of traditional remedies, almost all of which are based on extracts from plants and insects, and some major academic medical centers—the College of Physicians and Surgeons at Columbia University to name one—have set up departments of traditional medicine. It is hard to place even a rough value on biodiversity as a source of medical and agricultural information, but this is clearly a very large value indeed. In this sense biodiversity is a capital stock yielding a flow of services of at least several tens of billions of dollars annually. Little is new in this insight, incidentally: the recognition of the pharmaceutical value of biodiversity is simply a recognition of value in traditional healing practices. Societies have traditionally used plant and insect derivatives to treat illness; Shakespeare recognized this in *Romeo and Juliet*[22]:

> O! mickle is the powerful grace that lies
> In herbs, plants, stones and their true qualities:
> For nought so vile that on earth doth live
> But to the earth some special good doth give,
> Within the infant rind of this weak flower
> Poison hath its residence and medicine power.

Biodiversity also plays a critical insurance role. Its contribution to the maintenance of rice production provides an excellent example. Rice is one of the most important food crops in the world, and certainly the most important in Asia. Strains of wild rice are preserved as a source of genetic variation by the International Rice Research Institute (IRRI) in the Philippines, and the returns to this investment have been almost incalculable. In the early 1970s a virus called the grassy stunt virus posed a major threat to Asia's rice crop: it was expected to destroy 30-40% of the crop, bringing great hardship and economic loss. The threat was avoided by genetic engineering in which an immunity-conveying gene from wild rice was transferred to commercial varieties. For the record, the strain of wild rice containing

[22] *Romeo and Juliet*, II:iii. Cited in Gurr and Peach [47], which is an interesting and informative review of developments in plant-based pharmacology.

the ability to resist grassy stunt was located in the wild in only one place, a valley that was flooded by a hydro power dam shortly after it was collected. If the IRRI had been set up a few years later, we would have lost the ability to resist that virus and consequently lost much of the Asian rice crop.

A similar event occurred in 1976: another threatening disease was defeated by genetic manipulation that transferred to commercial varieties the immunity carried by certain strains of wild rice. So the investment in conserving genetic diversity has been responsible for maintaining the productivity of Asian rice farming.[23]

Environmental assets also have value as life-support systems: green plants produce the oxygen without which animals die. In fact, the planet's atmosphere originally contained no oxygen: oxygen was introduced by plants and microorganisms. Bacteria not only clean water but create and fertilize soil.[24] Insects pollinate plants and control agricultural pests.[25] All these activities are absolutely crucial in the maintenance of human life. Furthermore, the extent of these life-support activities is certainly not fully understood; recent theories hold that the destruction of ecosystems is contributing to the spread of new diseases to humans and to increases in the geographic range of traditional diseases.

On less speculative matters, it has been discovered that damage done to soil ecosystems by pollution has reduced their ability to purify water collected in aquifers and reservoirs, and so increased the need for expensive water purification plants. In cases such as this, it is well within the limits of our present methodology to assign a value to the services provided by environmental assets. For example, we can easily asses the cost of destroying the microorganisms that purify water as it passes through the soil. It is the cost of building and running water purification plants to provide the services once provided by the ecosystems. For the watershed of a large urban area, this can require an investment of tens of billions of dollars. This investment must be repeated as equipment wears out every few decades, with running costs in the interim. And even after all this expenditure, chemical purification is less satisfactory than the natural alternative. To give a concrete example, New York's water comes from a watershed in the Catskill mountains. Until recently the natural purification process, carried out by microorganisms in the soil, was sufficient to cleanse the water to Environmental Protection Agency standards. In recent years, sewage, fertilizer, and pesticides in the

[23] This example is taken from chapter 14 by Myers in Daily [33].
[24] See Daily, Matson and Vitousek, chapter 7 in Daily [33].
[25] See Naylor, Ehrlich and Ehrlich, chapter 9 in Daily [33].

soil reduced the efficacy of this process. As a result, the city was faced with a choice: it could either restore the integrity of the Catskill ecosystems that purify water or build a purification plant at a capital cost of $6-8 billion (about $1000 per adult in New York), plus running costs of the order of $300 million annually.

Restoring the integrity of the Catskill watershed meant buying land in and around the watershed so that its use could be restricted, and subsidizing the construction of better sewage treatment plants. The total cost of measures needed to restore the functioning of the Catskill watershed came to $1-1.5 billion. The cost of attaining the same outcome through a purification plant was $6-8 billion, an immense difference. So in this case investing $1-1.5 billion in the environment saved an investment of $6-8 billion in physical capital.[26]

In addition to these immensely practical values, environmental assets such as animals, plants, and even landscapes may have an intrinsic value, a value independent of their anthropocentric value, and they may have a right to exist independently of their value to humanity.[27] It is hard, if not impossible as a matter of principle, to place an economic value on such values and rights. Perhaps respecting them has to be seen as a constraint on society's economic activities, and we should not seek to trade them off against other goals.

Biodiversity may have great cultural significance for certain societies. This role is not restricted to traditional societies; examples are the bald eagle as a symbol of the United States, the bear as a symbol of Russia, or the relationship between Hinduism and the elephant. Biodiversity plays a crucial role in many social and cultural traditions and in forms of artistic expression. Many dimensions of expression, and many elements of social and cultural self-awareness, could be damaged by extensive loss of biodiversity.

All of these sources of value are critically important, as are others that have not been mentioned. However, there are distinctions. Information value and life support value are instrumental values and may vanish if we find synthetic substitutes for natural resources in these roles. They value the environment as a means rather than as an end. This is in contrast to recognizing a value intrinsic in environmental assets, irrespective of instrumental values.

Explicit recognition of all the contributions made to human societies by

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[26] For more details on this example, see Chichilnisky and Heal [27]

[27] A discussion of some of these philosophical issues can be found in Kneese and Schultze [62], Murphy [75] and Rolston [87]. A fascinating recent paper by Ng [77] is also recommended.

environmental assets seems an essential element of the concept of sustainability. How do we represent this analytically? In the economics literature on the optimal use of natural resources, the standard approach has been to include in the model a stock of a natural resource whose value at time t is denoted s_t, and to indicate that it is the consumption, the depletion, of this stock that contributes to welfare. Letting c_t be this consumption rate at date t, utility, production, or both are shown to depend on c_t. The dynamics of the natural resource also reflects its rate of consumption, so that for an exhaustible resource

$$\frac{ds_t}{dt} = -c_t$$

and for one that is renewable and whose growth is a function $r(s_t)$ of the current stock one has

$$\frac{ds_t}{dt} = r(s_t) - c_t$$

It is a clear implication of the literature on ecosystem services (see Daily [33]) that this formulation is inadequate, and that in many important cases the impact of environmental assets on economic well-being is a function at least as much of the existing stock as it is of the rate of consumption of that stock. Examples come to mind readily. A forest contributes to economic well-being by providing timber; the level of this contribution is measured by the rate of consumption of the forest. It also contributes to well-being by removing carbon dioxide from the atmosphere and producing oxygen. Here the contribution is a function of the size of the stock. A forest also contributes to well-being by acting as a climate stabilizer, as a shelter and support for biodiversity, and in many cases as a watershed, managing water flows and purifying water. In all of these roles, the extent of the benefit provided is a function of the stock. Of course, stock is a simplification here: the distribution of trees by age and species certainly matters, so that for a detailed representation stock should be a vector reflecting these characteristics.

Biodiversity is an environmental asset that contributes to economic welfare entirely as a function of its stock, rather than as a function of its rate of consumption. Viewed economically, biodiversity is an exhaustible resource: its depletion via species extinction or other loss of genetic diversity is irreversible, at least on human time scales. Thinking of depletion of biodiversity as consumption, we can see that there is no direct benefit from such consumption, although it may be a by-product of other valued activities. The benefits that we gain from biodiversity are a function of the extent of this diversity, suitably measured (i.e., of the size of the stock).

In the case of soil, what matters from the perspective of economic welfare is probably a combination of physical stock and productive quality. The physical stock certainly can be depleted via erosion by wind or water, and the productivity of a stock can be reduced by overcropping or misuse of agricultural chemicals.

Other cases are probably much more complex. In some cases, what gives the maximum contribution to economic well-being is a fully functioning, noncompromised and nondegraded ecosystem. The extent to which there are simple indicators of this state, whose dynamics can be related to economic activity, is an important and largely open research topic.

In my analytical modeling, I summarize this complex discussion quite crudely: in general I assume that utility is derived from a flow of consumption that can be produced from the environment and from the remaining stock, so that society's instantaneous utility at each point in time can be expressed as a function $u(c_t, s_t)$, where c_t is a flow of consumption at time t and s_t an environmental stock at that date, as in Krautkraemer [64] and subsequently in Beltratti, Chichilnisky, and Heal [12]. Of course, this is a heroic oversimplification. However, it is in the best traditions of growth theory, indeed economic theory in general, to take the first steps in exploring new issues by treating them in a very aggregative manner.

A natural next step in environmental research is to study more closely the technologies and processes by which the stock of an environmental asset provides value to the community. For example, in the case of biodiversity, the services are not a function only of the stock. If one thinks of the service of provision of knowledge, as discussed above, then the extent to which this service is provided depends on the stock and also on the resources allocated to biological prospecting. If one thinks of the recreational services of a forest, which clearly depend on the forest stock, then these also depend on transportation possibilities and accommodation possibilities. In general, for each category of service provided by environmental assets, there are processes by which this service is provided and complementary inputs involved in the provision of the service. Aggregative models of the type I review here do not and are not designed to capture these details; they are intended to provide insights at a more general level about the use and conservation of environmental assets.

1.7 The Analytical Framework

The remainder of this book proposes an analytical framework that is conceptually quite simple. The framework is one for modeling the dynamic interactions of economic and biological systems, studying the time paths that can emerge from these interactions, and then selecting one or more of these as in some sense optimal. Optimality is defined with respect to the current and long-term behavior of the path, and of course placing value on the contributions of environmental assets to economic well-being.

Symbolically, let e be a vector of economic variables and b be a vector of biological or ecological variables. Each has a dynamic that depends on its own values and those of the other:

$$\frac{de}{dt} \equiv \dot{e} = f(e,b), \ \frac{db}{dt} \equiv \dot{b} = g(e,b) \tag{1.2}$$

Of the paths satisfying the equations (1.2), some are sustainable and some not. A precise definition of sustainability will come later. Typically a necessary condition for a path to be sustainable is that the path is contained in a region that is bounded away from some of the coordinate axes: it is bounded away from some axes because we do not want some key variables to go to zero. These would certainly include the stocks of various biological assets. What kinds of paths stay in a region that is bounded and is also bounded away from some of the axes? Clearly nonzero stationary solutions to (1.2) meet this condition. Limit cycles can also meet this condition. So can chaotic attractors. So mathematically we are looking for stationary, periodic, or semiperiodic solutions to (1.2); these are the paths that might be sustainable, in the sense that they can be continued for ever without certain key variables going to zero. This framework captures the constraints imposed on economic activity by the environmental asset base. Within the universe of such paths, we then want to find those that are in some sense best. We need to devise a way of ranking the alternatives and then optimize according to this ranking. If we were to focus only on stationary solutions as possible sustainable paths, this would be a finite dimensional optimization problem: the analysis associated with what I call the green golden rule below falls into this category. More generally, it is a more complex infinite dimensional optimization problem.

1.8 Summary

If we value the longrun adequately, recognize the values of environmental assets, and recognize the constraints imposed on economic activity by their dynamics, then everything else that is generally associated with the concept of sustainability is logically implied. This approach will lead to the selection of what we think of intuitively as sustainable policy options when considering policies toward such complex long-term issues as global warming, species preservation, and the management of nuclear waste.

The key link in this argument is that valuing the longrun implies substantial concern for social costs that will occur one hundred years or more ahead, and hence a concern about the long-run consequences of climate change, nuclear waste disposal, and loss of biodiversity. Such concerns are rational only if we place more weight on the very long run than is consistent with the usual approach, namely discounted utilitarianism. So although valuing the longrun, valuing environmental assets, and respecting the constraints they place on us do not themselves describe precise sustainable policies on issues such as climate change and biodiversity, they are necessary conditions for the systematic and consistent selection of sustainable policies as optimal.

This framework is consistent with the attitudes of Bariloche, Brundtland, Daley, Pearce, Solow, and the other authors mentioned earlier, namely that sustainability is about intergenerational equity, resource constraints, and concern for the impact of human activity on the environment over the long run.

1.9 Outline

In the following chapters, I introduce and develop a framework for discussing the concept of sustainable development. I start from the premises already introduced, that there several simple but central elements to sustainability. One is placing sufficient value on the very long run, which means placing on the very long run a greater value than is done by the discounted utilitarian framework. Valuing the very long run appropriately is essential if we are to analyze issues such as global warming and the disposal of nuclear wastes, both of which may pose threats to human societies over very long time horizons, horizons running into hundreds of years. A second key element is recognizing explicitly the several sources of value associated with stocks of environmental assets, and in particular recognizing that these stocks may be valuable in their own right, and not just for the consumption goods they can yield. A third key element is recognizing the constraints placed on economic possibilities by the growth patterns of environmental resources.

I introduce simple dynamic economic models within which one can examine some of these matters. One model allows us to study the optimal use patterns for a resource that is exhaustible, but whose stock is a source of value. The second allows us to conduct the same exercises for a renewable resource; in each case we can enquire into the optimal use of the resource over time, given that its stock is a source of utility. Finally, we look at the problem of making an investment whose payoff may be very, very far into the future. Examples are investing to ensure the safe disposal of nuclear waste, investing to prevent global warming, or investing in a technology to produce a renewable alternative to fossil fuels.

Within each of these three scenarios, I study the optimal policy, the associated social valuations or shadow prices, and their implications for national income accounting and project evaluation. I do this using several alternative definitions of optimality: the conventional discounted utilitarian definition, a concept of optimality that involves attaining the maximum sustainable utility level and is a generalization of the golden rule of neoclassical growth theory (the green golden rule), a concept of optimality due to Chichilnisky that treats the present and the very long-term future quite symmetrically, and, when appropriate, the concepts based on the idea overtaking and on the intertemporal version of Rawls's concept of justice. The discounted utilitarian approach is present oriented, maximizing sustainable utility leads us to focus entirely on the very long run, and Chichilnisky's criterion combines aspects of both. Each of these three concepts of optimality is explored in each of the three modeling scenarios. Certain general results emerge from this exploration, particularly with respect to the impact of valuing stocks and valuing the longrun on shadow prices, project evaluation, and the appropriate definitions of national income and net national product.

I have arranged the material in the book in four parts: "Sustainability Within a Classical Framework," "A Broader Perspective", "Capital Accumulation", and "Policy Issues." The first part essentially applies the utilitarian approach to the set of models outlined above; this is supplemented by analyses of the implications of the golden rule and Rawlsian frameworks. It shows that even within this framework, there are interesting insights into sustainable management of natural resources. Recognizing that natural capital contributes to human welfare and that it has its own dynamic takes us a long way in the direction of selecting policies that accord with our intuition about sustainability.

In "A Broader Perspective", I try to come to grips with the insistence of Ramsey, Harrod, and their predecessor, Sidgwick, that future utilities should not be discounted. We look at Ramsey's stratagem for avoiding discounting, von Weizäcker's concept of "overtaking" as a generalization of Ramsey's program, and Chichilnisky's criterion, the only one to provide a framework as watertight and comprehensive logically as the utilitarian while going some way toward the Ramsey-Harrod-Sidgwick goal of treating present and future equally. Pursuing the implications of this criterion leads us into difficult problems technically and conceptually: technically because standard optimization techniques are not applicable, and conceptually because we are forced to grapple with some complex issues of dynamic welfare economics. However, these difficulties are rewarding: we narrow down more precisely the most productive formalizations of the concept of sustainability.

The chapters in "Capital Accumulation" show that none of the key conclusions of the previous parts depend on a key simplifying assumption of the model, the absence of produced capital. They revisit the earlier analysis in an economy in which produced goods can be invested in forming capital goods that to some degree may substitute for natural resources.

"Policy Issues" makes a preliminary attempt to set out the implications of all of the previous work for two key issues: how to measure national income in a dynamic resource-using economy (the issue often called green accounting) and how to pick the shadow prices used to value environmental assets in such an economy. In the discussion of national income accounting, I note that the approach most widely pursued to date, namely that based on the work of Fisher, Lindahl, Hicks [57], and Weitzman [100], has a quite different conceptual basis from that underlying the static welfare economics definition of national income. As noted above, a concept of sustainability is built into the Fisher-Lindahl-Hicks definition of income, a concept applied by Hicks to individual rather than national income. The more traditional welfare economics definition of national income, when extended to a dynamic framework, is quite distinct from this approach and is closer to a measure of national wealth rather than of national income.

1.10 Conclusions

Conclusions are usually found at the end of a book. I am placing them here because I want the nontechnical reader who dips into this book and does not go far beyond this introduction to be able to take away a sense of the destination we reach as well as the route we follow.

Many intellectually rigorous approaches to environmental management imply policies that are very conservative of natural capital. They range from approaches that are minor modifications of the standard discounted utilitarian approach to others that are radically more future oriented, such as the green golden rule. All produce optimal paths that could be implemented by decentralized behavior in a market economy, given suitable prices. And all have associated with them measures of national income that embody and reflect their underlying philosophies. The choice between them is ultimately a matter of social and individual values; whatever these are, within the range considered here, there is an economic framework to implement them.

These consequences of the alternative approaches can be listed under three categories: the effect on conservation of natural capital, the valuation of natural resources, and the measurement of national income.

1.10.1 Conservation

The smallest change we consider in the standard discounted utilitarian approach is including the stock of natural capital in the utility function, so recognizing that the stock of natural capital can affect human well-being directly. This is a part of the message from the ecosystem services literature. This move alone changes qualitatively the nature of an optimal path. For nonrenewable resources, which the standard approach would deplete completely, this alternative leads to situations where a portion of the initial stock of natural capital should be conserved indefinitely (chapter 3). The size of this portion depends on the discount rate. For renewable resources, it leads us to conserve a stock that exceeds that giving the maximum sustainable yield, improving the resilience of the system (chapter 4).

Going further and changing the optimality criterion in the direction of the green golden rule or Chichilnisky's criterion leads to still more conservative recommendations. The green golden rule can justify conservation of the entire initial stock of a nonrenewable resource, as will a Rawlsian approach. Chichilnisky's criterion can justify a significantly more conservative approach than usual, without going as far as the green golden rule (chapters 6 and 7).

1.10.2 Valuation

Again, simply recognizing that natural capital stocks can affect welfare directly has a significant effect: it leads to higher shadow prices or social valuations of natural resources. The other alternatives considered reinforce this effect. More future-oriented criteria lead to higher social valuations.

In some cases, the time paths of resource use that are optimal will not maximize the present value of profits at the associated shadow prices. Instead, they maximize sustainable profits, or a combinations of present value and sustainable profits (chapters 12 and 13). Maximizing sustainable profits means attaining the highest level of profits that can be maintained indefinitely: it is the equivalent for profits of the green golden rule.

1.10.3 National Income

Recognizing the importance of natural capital and of using more future-oriented criteria than the present value of utilities leads to significant departures from the standard measures of national income (chapters 11 and 12). In the context of environmental issues, researchers have pursued two different approaches to defining and measuring national income. One is based on the insights of Fisher, Lindahl, and Hicks, and has an intuitive consonance with sustainability. Another is based on the national income concept used in welfare economics and resource allocation theory. The two are distinct and involve different expressions for national income. The latter is more general and has variants that can be associated with each of the different approaches we consider, including in particular those other than discounted utilitarianism. It measures welfare in the same spirit as the standard national income measure of welfare economics, and in a dynamic context corresponds more to a wealth than an income concept.

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