SUSTAINABILITY AND ECONOMIC POLICY ANALYSIS

by

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ABSTRACT

The purpose of this dissertation is to provide a better economic basis for the discussion on how much natural capital the current generation should be allowed to deplete. Chapter I uses overlapping-generations models to show the effects of different assumptions about which generation owns the stock of a natural resource on the distribution of intergenerational welfare. An increase in the share of the resource stock that is owned by the first generation, reduces welfare of later generations. If the first generation owns the full resource stock, intermediate generations have to be sufficiently wealthy to buy the resource from the first generation and sell it to later generations. This channelling effect can lead to a situation of resource abundance followed by rapidly increasing resource prices and scarcity.

Chapter II show that the incompleteness of intergenerational insurance markets constitutes a market failure that leads to inefficient intergenerational investment decisions. Risks that increase from generation to generation would be under-insured by the current generation. Examples of excessive reduction of biodiversity, excessive natural resource depletion, and inefficiently low protection against global warming are provided.

Chapter III analyzes the decision theoretical foundation of environmental choices under uncertainty. Since ambiguity and ignorance are important aspects of many environmental problems, subjective expected utility theory (SEU) has significant limitations as a normative decision making model. The use of SEU leads to a systematic bias against the conservation of natural capital. An alternative decision model is suggested based on the Dempster-Shafer belief-function theory and Choquet expected utility.

The synthesis in chapter IV suggests that the costs of natural capital depletion are systematically underestimated in conventional analysis. To remedy the biases against future generations and the complete valuation of natural capital, a sustainability constraint on the economic activities of the current generation is proposed. This constraint requires compensation for natural capital depletion through functional substitutes. From this sustainability constraint, an operational sustainable supply rule is derived for determining shadow prices of natural capital depletion.

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We do not inherit the earth from our grandparents.

We borrow it from our children.

INTRODUCTION

Scientists estimate that between 10 and 80 million different species are inhabiting this planet. One of these species has experienced a particular remarkable development during the last two-hundred years. The human species experienced a technological revolution that led to an explosion of its global population and a dramatic increase of its ability to consume its environment, including other species on the planet. It takes a moment of reflection and contemplation to realize the extent of the changes to the face of this planet that the activities of human beings have brought about during a time span that is minute in the time scales of natural history. A large share of the land surface has been converted from wildlands to agriculture or forestry monoculture. As a result of rainforest destruction alone, more than 50,000 species annually are estimated to disappear (see Worldwatch Institute 1988, p.101-117). Anthropogenic emissions of carbon dioxide and other trace gases have reached a quantity that has the potential to drastically alter the global climate. The list of significant human impacts on the global environment has become rather long. The increasing evidence of long-term, and often irreversible, global environmental impacts of human economic activities is summarized, for example, in the Brundtland Report (World Commission on Environment and Development 1987) and the annual volumes of the Worldwatch Institute (1984-1993).

Human welfare has always depended on the natural environment. Historically, however, this dependency was one of submission and limited human capacity to harness and utilize the forces and resources of nature. The industrial revolution and the population explosion has radically changed the type of human dependency on nature. The size of the human population and the extent of human activities used to be small in scale compared to the size of the biosphere. However, human population and technology have grown in an unprecedented way, and phenomena such as the greenhouse effect, ozone layer depletion and ocean pollution have made apparent that the scale of human activities has now become comparable to the scale of services provided by the environment. For example, today humans use about 40% of the net primary product of land-based photosynthesis (see Vitousek et al. 1986). Increasingly, signs are emerging that we have moved from an "empty world" to a "full world" (see Daly 1991). Moreover, considering the inequality of consumption levels between people in different parts of the world and the desire of the population in many parts of the world to substantially increase their consumption of material goods, it is likely that crowding effects with regard to the natural environment will further increase and not decrease in importance.

For a long time, economists have analyzed economic interactions, human behaviour, and human welfare with theoretical models. Most economic theory was developed based on simplifying assumptions suitable for an empty world, abstracting from the physical realities of the natural environment to a very large degree. Only in those instances where the natural environment provided services that were considered scarce, relative to the human capacity to use them, economic subdisciplines have evolved that analyze scarcity and depletion of individual components of the natural environment, such as land economics, environmental economics, and resource economics. Beyond these specific sub-disciplines, the environment was often not explicitly considered in economic modeling. Undoubtedly, the world has changed. In a full world, there are many more interactions between economic activity and human welfare through the natural environment. Under these changed conditions, different simplifying assumptions are appropriate for economic modeling. It will not be appropriate to abstract from the natural environment as often as in the past.

Economists are often perceived to be engaged in an inherent conflict with environmentalists. This perception is unfortunate. The underlying philosophical objective of (normative) economics is the maximization of human welfare. Human welfare, however, depends to a large, and probably increasing, degree on the health of the natural environment. While there are many differences in thinking, there is no inherent conflict between the objectives of economists and most environmentalists. However, conflicts are often unnecessarily brought about by economic models that, inappropriately, abstract from important factors of the natural environment. In fact, the economic approach can provide many useful tools for making rational trade-offs and choices between different actions that impact on human welfare and give guidance in determining the most efficient way for achieving an objective such as a healthy natural environment.

The debate about economic growth illustrates the sometimes unnecessary conflict between economists and environmentalists. Environmentalists often accuse economists of promoting economic growth at the cost of future living conditions on the planet. They, rightly, point out that the physical resources of the world are finite and physical consumption can therefore not grow infinitely. Of course, the objective of economics is not to promote physical consumption, or economic activity, for its own sake but to maximize human welfare, which depends on consumption of physical and nonphysical goods as well as the conditions of the natural environment. Economists have often contributed to the conflict by abstracting from the difference between human welfare and physical consumption or measures of economic activity, such as GNP. Clearly, the objective of human welfare would include the concerns of most (certainly not all) environmentalists. Fortunately, the debate and the positions of either side are more diverse than portrayed here. Nevertheless, the described misunderstanding appears typical.

This dissertation is one of many attempts to develop economic models that are more appropriate for the full world in which we are living today. In particular, this dissertation deals with two important effects that result from a crowded world. The first effect is that humans have gained the capacity to influence long-term living conditions on a global scale. As a result, economic activities of the current generation have a significant impact on the welfare of future generations through the conditions in which we pass on the natural environment to our successors. This means there is a need to systematically examine the intergenerational welfare effects of our dealings with the natural environment. The second effect is that in an empty world externalities were the exception. In a full world, however, almost all economic activities are associated with external effects. Consider as an example a community located at a river. In an empty world, it would have been sensible to dispose of the community's waste products in the river. Chances would have been that no damages resulted since the waste products were diluted and little use was made of the river's water downstream. If some damage was done, one could deal with this on a case by case basis. This is the typical approach economists have taken in analyzing externalities. In a full world, though, waste products would aggregate from many communities and water would be used downstream. It is quite likely that any waste disposed of in the river would be delivered at some point where it causes damage. The case where no externalities would result from a polluting activity would be the exception in a full world. As a result of this pervasiveness of externalities, a different modeling approach would be indicated in many instances.

This dissertation is relatively broad in scope and, therefore, draws from the literature in a large number of areas. The pertinent literature will be briefly reviewed in the respective chapters. However, a few comments about the development of economic theory in relation to environmental problems will be offered in this introduction. Economists have long been concerned with the scarcity of natural resources. Malthus (1798) wrote the most cited early work on the conflict between finite natural resources (agricultural land in this case) and the growth of the human population. Since then, the debate has led to cyclical interest in the issue of natural resource depletion, depending on whether resource discoveries and increasing substitution possibilities were considered to be able to offset consumption growth. The single most important contribution to modern resource economics was made by Hotelling (1931) who introduced the user cost concept and compared resource depletion resulting from profit maximizing owners with welfare maximizing social planners. This theory of non-renewable resources has later been expanded to renewable resources (see Conrad and Clark 1987).

While resource economics is primarily concerned with the management of finite resources that are often privately owned, environmental economics focusses on problems of externalities and the design of policies to remedy the market failures resulting from externalities. A seminal contribution was made by Pigou (1932), who introduced the concept of charging a price for an externality that would equal the marginal costs of the externality. Other important contributions were made by Bator (1958), who defined the market failure resulting from an externality, Coase (1960), who emphasized the possibility of an efficient negotiation solution when property rights are assigned in cases such as pollution, and Dale (1968), who suggested the introduction of marketable emission permits. A good overview of the issues is provided in Baumol and Oates (1988). The extensive literature on the evaluation of environmental costs (for example in cost-benefit analysis) can, in part, be viewed as an extension of the work of environmental economists (see, for example, Pearce and Turner 1989).

Environmental and resource economists have applied standard economic modeling approaches to issues involving the natural environment. Recently, criticism has increased that this approach is insufficient to deal with the problems of an increasingly full world. Disillusioned with the high degree of abstraction from physical realities in economic models and the isolated treatment of individual resources or environmental problems, some economists have attempted more fundamental modifications to economic models in order to better reflect the nature of current environmental problems. Work following this approach is now often referred to as ecological economics. The development of ecological economics can be related, among others, to contributions by Georgescu-Roegen (1971), Daly and Cobb (1989), and Daly (1991). A good overview of this branch of research is given in Costanza (1991). Two central concepts of the ecological economics literature are of central importance for this dissertation. In order to overcome the limitations of the isolated treatment of individual resources and environmental problems, the concept of natural capital has been introduced. In order to address the inter-temporal, and particular intergenerational, dimension of environmental and resource problems, the concept of sustainability is now widely discussed.

The combined capacity of all components of the natural environment to provide services that can generate economic benefits is defined as natural capital. Natural capital includes natural resources, such as fossil fuels, minerals, forestry and fishery, the capacity to absorb wastes from human activities in limited quantities and the overall life support system of the planet including, for example, the atmosphere that provides the air we breathe and the ozone layer that protects us from harmful ultraviolet radiation. The biosphere as both a source of materials and energy and a sink for waste products represents natural capital. Natural capital is distinct from other, human-made, forms of capital in that it has not been created through conscious human efforts. Therefore, benefits from the existence of natural capital are often pervasive and its efficient use needs to be ensured through the establishment of property rights or mechanisms for efficient collective action. On the other hand, natural and human-made capital are similar in that they can suffer depreciation and depletion through use. The term natural capital is used to direct attention to the analogy with human-made capital: capital represents a stock of assets from which services can be derived. Like human-made capital, natural capital is more than an aggregation of individual assets or separate resource stocks. It is a complicated web of interrelations between assets and processes that, as an aggregate, provides a wide variety of services to humans.

Sustainability has become a popular concept in the discussion on inter-temporal and intergenerational welfare distribution. In its most common definition, "...sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their needs" (World Commission on Environment and Development 1987). While having intuitive appeal, this definition is very far from being operational in an economic policy or modeling context. Some attempts have been made to translate the concept of sustainability into economic terms (see El Serafy 1989 for an application to national income accounting and Pezzey 1989 for a variety of growth theoretical definitions of sustainability). In economic terms, sustainability is mostly understood as a constraint on the current generation's economic activities, requiring a non-declining level of consumption or utility for all future generations. However, real life uncertainties make the precise definition of such a constraint far from obvious. This dissertation contains an attempt to develop and refine a definition of sustainability that would be more operational for economic policy making. While sustainable human activities are those which use natural capital within its capacity to regenerate, this dissertation deals with activities that go beyond that limit, deplete natural capital and reduce the earth's capacity to serve as source and sink for welfare generating activities in the future.

The purpose of this dissertation is to contribute to a more solid economic basis for the discussion on how much natural capital the current generation should be allowed to deplete and whether, and how, future generations should be compensated for natural capital depletion. This dissertation consists of four chapters. The first chapter analyzes the effects of different assumptions about which generations own the stock of a natural resource on intergenerational welfare distribution. The second chapter analyzes the incompleteness of intergenerational insurance markets as a market failure that results in inefficient intergenerational investments under risk. The third chapter reviews and discusses the suitability of different decision making models for environmental decision making under real-life uncertainties. Finally, the fourth chapter proposes an operational sustainability constraint on the economic activities of the current generation as a robust rule for intergenerational compensation under uncertainty. An application of such a sustainability constraint to project evaluation is presented.

This dissertation is theoretical rather than empirical in nature. The purpose of the first two chapters is to show the importance of explicit consideration of intergenerational problems in the analysis of natural capital depletion. Both chapters use simple general-equilibrium overlapping-generations models. In these two chapters, a standard economic modeling approach is applied to new problems with quite interesting results. The methodology of chapters three and four is different. Their purpose is to explore the limitations of standard economic modeling approaches and modify more basic assumptions of standard models rather than apply standard models to a new problem. Chapter three questions the validity of the standard modeling approach for normative decision making under uncertainty and suggests an alternative. Chapter four presents the argument that, in practice, following a standard efficiency approach for environmental problems leads to systematic biases that imply sub-optimal decision making.

The different methodologies used in different chapters imply a different style of presentation as well. The first two chapters are based on the analysis of a problem with mathematical models, and results are presented in a formal manner. The third chapter questions standard modeling assumptions and focusses on a review of alternative modeling approaches rather than on the development of new theory. The fourth chapter, finally, contains a synthesis of results from the other three chapter. The focus of the fourth chapter is on the limitations of formal analysis. Subsequently, the exposition is less formal in itself and contains many conjectural elements. During the work on this dissertation, different degrees of progress were made on different aspects of the overall topic of sustainability and economic policy analysis. I have chosen to include in this dissertation material at very different stages of development (formal analysis, review, and conjectural synthesis). As a result, I hope, this dissertation includes a more complete view of the addressed problems rather than only the isolated presentation of a few polished results.

There are very many important and interesting questions relating to the topic of this dissertation. Naturally, I was neither able to deal with all of them nor in a position to make significant progress on more than very few of them. Therefore, many questions that are relevant to the topic are not addressed in this dissertation. Despite this dissertation's focus on intergenerational interactions, it does not include a thorough discussion or analysis of intergenerational ethics. Here, a standard economic approach is pursued. The impacts of certain actions or institutions on intergenerational welfare distribution are analyzed. Also, institutional arrangements for the implementation of certain value judgements about intergenerational equity are suggested. However, very little will be said about the basis for these intergenerational value judgements. There is, of course, an extensive philosophical debate on issues of intergenerational justice. However, this debate itself is considered outside the scope of this dissertation and only some references to it are made in the analysis. Beyond that, appeals to intergenerational justice are based on intuitive arguments.

The following paragraphs provide a brief overview and outline of this dissertation. Chapter I emphasizes the importance of distributional considerations between generations in the depletion of natural resources. The first part of that chapter uses different overlapping-generations general equilibrium models to analyze the effects of different assumptions about which generation owns the stock of a natural resource on the intergenerational welfare distribution. In simple consumption and production models, it is shown that increasing the share of the resource stock that is assumed to be owned by the first generation reduces the welfare of later generations. If the first generation owns all of the resource stock, subsequent generations have to be sufficiently wealthy to buy the resource from the first generation and sell it to later generations. This channelling problem leads to a constraint on resource consumption of all future generations that is determined by the wealth of the first two generations alone. If ownership of a resource by future generations is desired for justice reasons, but access to the resource by early generations is desired for efficiency reasons, early generations would have to explicitly compensate later generations for resource depletion.

The second part of chapter I analyzes a continuous time model of inter-generational resource depletion and suggests a pricing mechanism for the implementation of inter-generational compensation that would bring about constant utility across generations. Every generation would be allowed to purchase the resource at an administered, efficient, price. The proceeds would be invested in perpetuity and the returns to this compensatory investment would be used to augment the current generation's endowment. The model shows that in an inter-generational world, constant welfare across generations can be achieved through Hartwick's rule (invest all competitive resource profits) only if the resource price path is administered or if all generations have common knowledge about Hartwick's rule being observed by all future generations.

Chapter II uses an overlapping-generations model to show that the incompleteness of intergenerational insurance markets constitutes a market failure that leads to inefficient intergenerational investment decisions under risk. Early generations over-diversify if they face risks that are larger than those of the following generation and could, therefore, be shared with them. On the other hand, if risks are increasing from generation to generation, the current generation would under-insure against those risks. Furthermore, a generation with decreasing risk aversion would, in many cases, over-consume a natural resource if the resource-stock uncertainty is larger for future generations. The main message of this chapter is to caution against the belief that markets work efficiently to transmit across generations the right signals for economic decisions under risk. The larger the social risks involved, the more reason there is to believe that markets do not bring about efficient decisions by the current generation. The direction of the inefficiency, however, depends on the nature of the risk assumed. Therefore, the policy implications that can be drawn from this chapter depend on the empirical assessment of the risks that current and future generations are facing. This chapter also provides applications of the general result to environmental problems such as the reduction of biodiversity, protection against global warming and the depletion of a natural resource.

Chapter III analyzes the decision theoretical foundation of environmental choices under uncertainty. Environmental decision making involves choices about the depletion of natural capital, i.e., choices about resource depletion, emissions, land use, and other issues. Many of these choices involve large uncertainties that are not well captured by modeling them as risks. Risk is defined as a situation of uncertainty with a known probability distribution over a well defined set of states of the world. In particular, it is often impossible to assign a probability distribution over all states of the world, which is the case of ambiguity, or it is impossible to describe all states of the world completely, which is the case of ignorance. The standard model for decision making under uncertainty is the subjective expected utility model (SEU) which is a theory that models uncertainty as risk. Chapter III is motivated by the belief that, by abstracting from ambiguity and ignorance, SEU assumes away critical aspects of many environmental decision making problems. It is argued that, since SEU is not applicable to situations of ambiguity and ignorance, has significant limitations as a normative model for environmental decision making.

The focus of chapter III is the review of alternative models of decision making under uncertainty and suggestions for a model that is more suitable for normative environmental decision making than SEU. The purpose of the discussion is to analyze existing models and combine elements of those models in order to provide a decision theory that is of practical use for environmental decision making. The chapter begins with an analysis of the conceptual and practical problems of using SEU and reviews several relevant alternative models of decision making under ambiguity and ignorance. Then, an alternative decision making model is suggested based on a combination of the Dempster-Shafer belief-function theory and Choquet expected utility. This proposed theory is illustrated by means of an example. It is shown that, compared to the proposed theory, the use of SEU in decision problems with ambiguity leads to a systematic bias against the conservation of natural capital.

Chapter IV provides a synthesis of problems dealt with in the other chapters. The discussion shows that, in conventional economic analysis, the costs of natural capital are systematically underestimated due to individual short-term incentives of decision makers, the presence of externalities and large uncertainties about the functioning of the biosphere. In addition, decision making is systematically biased against the interests of future generations. Intergenerational efficiency and justice require that future generations be actually, not only potentially, compensated for costs imposed on them by previous generations. To remedy the biases against proper valuation of natural capital and to reflect a cautious approach toward depletion of natural capital, it is proposed that the default value of natural capital should be the cost of providing a sustainable substitute. The rents from depletion of natural capital should be shared equally with all future generations who need to be adequately compensated for depletion. Following from these considerations, this chapter proposes a sustainability constraint on current economic activities. This constraint would require that the value of every group of functionally substituting types of natural and human-made capital be left intact in the sense that a sustainable stream of services can be derived from it. The sustainability constraint should be reflected in the shadow prices used to evaluate natural capital depletion, for example in cost-benefit analysis.

From the sustainability constraint, an operational sustainable supply rule is derived that can be applied to the depletion of non-renewable resources and the consumption of the biosphere's limited capacity to absorb waste products. This rule requires that a sustainable price, derived from a sustainable supply curve, be used for depletion of natural capital. The sustainable supply curve is constructed by dividing the economic rents from the depletion of natural capital into an income and a compensation component. The compensation component must be invested into the production of the closest sustainable substitute for the depleting natural resource. The compensation component should be sufficient to provide the same quantity of the sustainable substitute at the sustainable price forever after depletion. The income component could then be sustained after depletion. The sustainable supply rule is applied in a stylized case study of an oil development project, and the impacts for the evaluation of the project are shown.

CHAPTER I

THE DEPLETION OF NATURAL CAPITAL AND INTERGENERATIONAL WELFARE

1 Introduction

Resource economists have examined in great depth the question of whether markets bring about intertemporally efficient resource depletion. The modern stream of inquiry to this question goes back to the seminal paper of Hotelling (1931). The main result is that competitive markets for privately owned resources will lead to efficient resource depletion with a resource price rising at the rate of interest. The theory of natural resources has since been integrated with macroeconomic growth models describing feasible growth paths in the presence of natural resources. In addition, it has been recognized that the depletion of natural resources leads to implications for welfare distribution across time. In general, there are many efficient resource allocations with very different distributions of intertemporal welfare. Based on the definition of an explicit social welfare function, one can determine the optimal resource allocation, which is the one that maximizes social welfare. Models for choosing the optimal allocation among all efficient intertemporal resource allocations through maximization of a social welfare function have been developed to analyze distributional concerns (see Dasgupta and Heal 1974, Solow 1974, Stiglitz 1974, and also Dasgupta and Heal 1979, pp. 255-359, chapters 9 and 10). In this context, particular attention has been paid to a maximin social welfare function. Hartwick (1977), Dixit, Hammond and Hoel (1980) and Solow (1986) analyze the conditions under which a maximin welfare path would be obtained. Their main result is "Hartwick's rule" stating that if net-investment equals resource profits at competitive prices, a constant welfare level will be obtained.

Most models of optimal resource depletion are based on a managed economy with exogenously determined levels of investment and consumption. Hence, there is little work addressing the question under which circumstances markets would bring about not only efficient but also optimal resource depletion. However, since investment and savings decisions are decentralized at least to some extent in most real life economies, it would be important to develop a better understanding of the possibilities to implement optimal depletion paths in a decentralized economy. This requires a microeconomic modeling component including the savings and investment choices of short-living individuals. In an intergenerational context, this is the natural realm of overlapping generations models as pioneered by Samuelson (1958). However, natural resources were notably absent from overlapping generations models until the very recent contributions of Howarth and Norgaard (Howarth and Norgaard 1990, Howarth 1990, Norgaard and Howarth 1991). In a simple two-generation framework, Howarth and Norgaard (1990) show the crucial difference between efficient and optimal resource depletion paths and the importance of assigning resource property rights to different generations according to the chosen social welfare function. They show in an inter-generational context the dependency of welfare and prices on the endowment distribution, which is well understood in a static general equilibrium setting.

The first part of this chapter contains several extensions of the Howarth and Norgaard model. The models analyzed and presented here are more general and include production, more than two overlapping generations, the existence of a renewable resource and a varying share of expenditures on the natural resource. The extension to a production economy is obviously important to reflect resource use in the real world. The extension to renewable resources would include many urgent environmental problems such as the greenhouse effect or ozone layer depletion, which can be modeled as depletion of a renewable absorption capacity for emissions. The models are used to analyze the endowment effect, which biases welfare in favour of those generations assumed to be endowed with the natural resource. The extension to more than two generations will prove to make an important difference since non-adjacent generations are not able to trade with each other directly. This results in a channelling effect, which limits the extent to which the demand of distant generations is able to influence resource prices at earlier times. The second part of this chapter addresses the question how a desired welfare distribution can be implemented in a decentralized economy. A continuous time, multiple generations model is used to analyzes the possibilities to implement a sustainable resource depletion path through a pricing mechanism that requires early generations to explicitly compensate later generations for resource depletion.

2 Natural Resource Endowments and Intergenerational Welfare

Market economies are based on private ownership and market exchange of resources. The first theorem of welfare economics states that the competitive equilibrium, following from such market exchanges under certain conditions, is efficient (see Varian 1978). Of course, the welfare distribution between individuals depends on the initial distribution of ownership (or the endowments). As a result of unequal endowment distribution, an efficient equilibrium may imply gross welfare inequalities. In this section, these simple ideas are applied to different generations' ownership of natural resources. Under current institutional arrangement, a resource is either publicly or individually owned by members of the current generation. This chapter, however, uses the hypothetical construct of explixit ownership of parts of the resource by future generations in order to provide a model that can be used to analyse normative questions about depletion rates and their impact on intergenerational welfare. The question which institutions could be used to implement the ownership of resources by future generations is deferred to chapter IV and not addressed in this chapter. With this perspective, I will explicitly analyze the implications of different assumptions about which generation owns a share of the natural resources for intergenerational welfare.

In the real world, there are at least two channels through which a generation passes on assets to its successor generation. First, there are market transactions between overlapping generations. For example, a capital stock is accumulated by an early generation through savings. At retirement age, these investment assets are sold to a younger generation against consumption goods (e.g. by selling stocks out of a pension fund). Second, early generations bequeath assets to later generations. The models in this chapter focus on market interactions between generations and abstract from intergenerational wealth transmission as the result of intergenerational altruism. It is assumed that every generation maximizes utility from own consumption only. The reason for making this assumption, despite evidence that individuals within any generation do not maximize utility from own consumption alone but care about the well-being of their off-spring as well, is that it focusses the analysis on the distributional conflict between generations.

In this chapter, optimality is discussed in terms of an intergenerational social welfare function. However, the utility function of individual generations in the models does not include a bequest motive. This approach may appear paradoxical since it supposes the existence of a social welfare function that is in this respect independent of the current generation's preferences. Two independent justifications for this approach are provided in the following paragraphs. The first justification is based on coordination failures and public good problems involved in intergenerational altruism that would lead to inefficiently low individual provisions for the welfare of future generations. The second justification is based on the possibility of dual objectives of the current generation: a selfish utility function for individual choice and a moral welfare function for social planning.

There is a significant body of literature examining the question whether individual bequest motives can lead to welfare optima (see Barro 1974, Bernheim 1989, and for a summary Blanchard and Fisher 1989, pp 104-110). The possibility of a welfare optimum depends critically on the specific way in which intergenerational altruism is modeled (one-sided altruism, two-sided altruism or a bequest motive). Under highly restrictive conditions, a succession of distinct generations behaves like one infinitely lived generations, whose utility function would then be logically taken as the social welfare function (see Blanchard and Fisher 1989, p.97). In most circumstances, however, intergenerational altruism, whether it is caring about the well-being of own descendants or about future generations in general, does not lead to a welfare optimum due to public good problems and coordination failures.

The public good problem of caring about one's own descendants has been explained by Daly (1982). The number of descendants one cares about would rise exponentially with every generation. Specifically with a constant population, every individual would have 2^n descendants in the n^{th} generation. Conversely, every individual in the n^{th} generation would have 2^n individuals in generation zero who care about her/his well-being. Unless efficient mechanisms for collective action by co-progenitors are in place, there would be under-investment in the well-being of future generations because of the public good nature of such investment: the well-being of one's great-grand child would depend on the provision of eight co-progenitors. Everyone would try to free-ride on the provisions of seven co-progenitors, and the result would be sub-optimal investment. Coordination mechanisms would be extremely difficult to arrange since, for provisions for distant generations, the individuals with whom one would have to coordinate are not yet identified.

The public good problem is even more obvious if individuals in the current generation cared not about their individual descendants but about the well-being of future generations in general (see Marglin 1963). Again, individuals would inefficiently under-provide resources for future generations. It may be added that some social institutions have traditionally served to alleviate this public good problem. Such social institutions include the concept of responsibility toward the "seventh generation" in North American native ethics as well as European family traditions according to which all family property was passed on to the oldest son instead of being divided between siblings. This tradition can be seen as not only preserving family estates but also making it easier for earlier generations to identify themselves with a single line of descendants and thereby avoiding the discussed public good problem. The decline of the importance of extended families shows how some of these social institutions have lost their influence through social changes.

In the presence of one of these public good problems, individual action based on intergenerational altruism would be inefficient. Hence, one justification for abstracting from intergenerational altruism is that the concerns about intergenerational welfare distribution cannot be overcome by individual action based on intergenerational altruism alone. Based on this justification, this chapter would provide analysis for determining the desired collective action to overcome the public good problem of intergenerational altruism. Also, the effect of intergenerational altruism has been explored in similar models before (see Howarth 1990, pp. 62-76, chapter IV) leading to the discussed public good problem.

A second justification for supposing the existence of an intergenerational social welfare function, independent of the first generation's preferences, can be found in the extensive literature on the duality of human objectives. Harsanyi (1953), Margolis (1982), Sen (1985), and others describe human objectives as dual in the sense that individuals have moral objectives, often related to fairness considerations, that are not reflected in daily individual choices. However, these moral objectives are used in making long-term choices about social institutions and are often delegated to government action (see also Rawls 1971). Based on such dual model of human objectives, the utility functions that determine individual choices would exclude considerations of intergenerational fairness. The objective of intergenerational fairness would, however, be reflected in a social welfare function that is used to determine the optimal intergenerational welfare distributions.

2.1 The Endowment Effect

The two main effects resulting from different distributions of resource endowments across generations are discussed in different sub-sections on the endowment and the channelling effect. The present subsection is devoted to the exposition of the endowment effect which describes the welfare effect of endowing different generations with the stock of natural resources. The endowment effect would be present even if all generations were living at the same time. The next subsection will address the channelling effect which arises because of the particular intergenerational structure that implies that not all generations can trade with each other directly.

Several similar models will be used to explore the welfare effects of changing the assumptions about which generation owns how much of the resource stock. These models

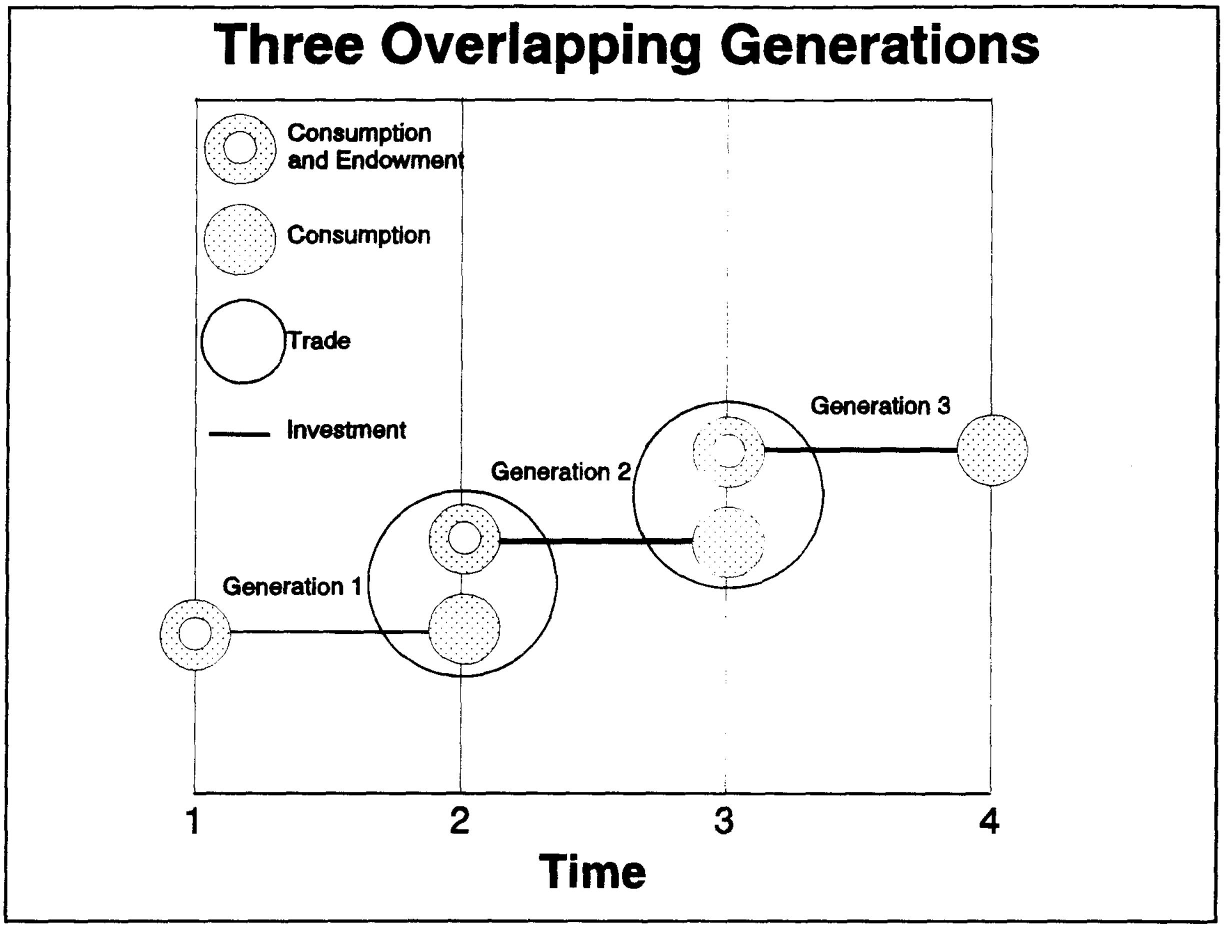

Figure 1.1 The Structure of the Overlapping-Generation Models

should capture the possibility of trade between adjacent generations but also the absence of markets between generations that are further apart in time. Hence, an overlapping generations model in which only two adjacent generations overlap at any one time is selected. In order to allow trade and substitution between the natural resource and other goods, the models include a second generic investment and consumption good which every generation is endowed with. In order to be able to explicitly solve for the equilibrium, specific functional forms for utility and production functions are used in the models. In the first model, agents consume both the natural resource and the consumption good. For simplicity, the rate of return on investment of capital is assumed to be constant. After a solution to the n-generation model is found, the equilibrium welfare of the generations is analyzed with respect to changes in resource endowment and rates of return. A second model captures the impact of more realistic production possibilities. In that model, agents consume only one consumption good which can be produced from capital and the natural resource with an endogenous rate of return. The overall structure of the models is shown in Figure 1.1 for an example with three generations.

2.1.1 An N-Generation Consumption Model

There are two goods in the economy: K is a generic consumption and investment good (the capital good) with a constant rate of return, α-1. Hence, one unit of K invested at time t = i yields α units of K at time t = i+1 (normally $\alpha > 1$). R is a natural resource with a constant rate of reproduction β-1. One unit of R left behind at time t = i yields β units of R at time t = i+1. For a non-renewable, non-perishable resource β would equal one. There is a finite number of generations i = 1,2,...,N, each of which is modeled as one representative agent. Generation i lives at times t = i and t = i+1 and consumes R and K at both times. The utility function of generation i is:

$$U_i = z\,Log[K^c_{i,i}] + (1-z)\,Log[R^c_{i,i}] + \delta\left(z\,Log[K^c_{i,i+1}] + (1-z)\,Log[R^c_{i,i+1}]\right) \quad \textbf{(1)}$$

where $(K^c_{1,2}, R^c_{1,2})$ would denote generation 1's consumption at time 2. δ is the utility discount factor and z ($0 < z < 1$) represents the relative importance of the capital good compared to the natural resource. This specific form of the utility function is chosen because it allows derivation of simple explicit equilibrium solutions. Also, log-utility can be obtained from the more common Cobb-Douglas form, $(K^c_{i,i})^z(R^c_{i,i})^{(1-z)}$, by a simple monotonic transformation. Generation i receives an endowment (K^e_i, R^e_i) at time i. K^e_i can be thought of as labour endowment with labour being able to produce K on a one to one basis. The total initial stock of the resource, S_0, is fully distributed as endowments. Hence:

$$\sum_{i=1}^{N} \frac{R_i^e}{\beta^{i-1}} = S_0 \quad \textbf{(2)}$$

Generation i invests K^i_i and R^i_i at time i. At every time i, the old generation, i-1, and the young generation, i, can trade R for K at price p_i (K is the numeraire good with prices in current terms). Generations are assumed to behave competitively. There is no uncertainty, and generations have perfect foresight.

Generation i maximizes its utility, U_i, by choice of consumption, $K^c_{i,i}$, $R^c_{i,i}$, $K^c_{i,i+1}$, and $R^c_{i,i+1}$, and investment, K^i_i and R^i_i, subject to budget constraints at time i and i+1:

$$\begin{aligned} K_i^e - K_i^i - K_{i,i}^c + p_i(R_i^e - R_i^i - R_{i,i}^c) &= 0 \\ \alpha K_i^i - K_{i,i+1}^c + p_{i+1}(\beta R_i^i - R_{i,i+1}^c) &= 0 \end{aligned} \tag{3}$$

Investments cannot be negative ($K^i_i \geq 0$ and $R^i_i \geq 0$). Since these non-negativity constraints are not included in the maximization problem, they have to be verified once a solution is found. Corner solutions to the problem will be discussed in a separate section. The model can be solved with one market clearing condition for every time t = 2,...,N:

$$\beta R_{i-1}^i + R_i^e = R_{i-1,i}^c + R_{i,i}^c + R_i^i \tag{4}$$

The derivation of demands and prices is shown in Appendix I-A.[1] For the interior solution ($K^i_i > 0$ and $R^i_i > 0$), prices are:

$$p_i = \frac{\alpha^{i-1}(1-z)\sum_{j=1}^{N}\frac{K_j^e}{\alpha^{j-1}}}{\beta^{i-1}z\sum_{j=1}^{N}\frac{R_j^e}{r^{j-1}}} = \frac{\alpha^{i-1}(1-z)\sum_{j=1}^{N}\frac{K_j^e}{\alpha^{j-1}}}{\beta^{i-1}zS_0} \tag{5}$$

and demands are:

[1] The solutions to the maximization problems in chapters I and II were obtained using Mathematica, Version 2.0, as described in Wolfram (1991).

$$K_{i,i}^c = \frac{(K_i^e + p_i R_i^e) z}{1+\delta} \qquad R_{i,i}^c = \frac{(K_i^e + p_i R_i^e)(1-z)}{p_i(1+\delta)}$$

$$K_{i,i+1}^c = \frac{\alpha\,\delta\,(K_i^e + p_i R_i^e) z}{1+\delta} \qquad R_{i,i+1}^c = \frac{\beta\,\delta\,(K_i^e + p_i R_i^e)(1-z)}{p_i(1+\delta)} \tag{6}$$

Equation (5) implies $p_{i+1} = (\alpha/\beta)\, p_i$, which for a non-renewable resource ($\beta = 1$) is the well known Hotelling price path. For interior solutions, the price path in equilibrium depends only on the present value of total endowments and not on the distribution of the endowments. As a result of the assumed log-utility, the demands reflect a fixed share of expenditures on each of the four consumption goods with demand changing over time at the rate $\alpha\delta$ and $\beta\delta$ for the capital good and the resource respectively.

Proposition 1.1: **If, in equilibrium, all generations i invest a strictly positive amount of capital and resource at time i, the competitive intertemporal resource allocation is efficient. Hence in an interior solution, the absence of markets between non-adjacent generations does not introduce an inefficiency.**

Proof:

All market clearing conditions taken together imply that the resource is completely used up. Full depletion of the resource and the Hotelling price path are sufficient conditions for intertemporal efficiency of resource use in the simple consumption economy of this model (see Dasgupta and Heal 1979).■

2.1.2 The Two-Generation Case

Several important observations can already be made in the simplest possible setting of a two-generation model (N=2). With two-generations, trade takes place only at t=2 between generations 1 and 2. The first result was shown before by Howarth and Norgaard (1990) for $\alpha = 0$, $\beta = 1$ and $z = 0.5$. In general form it is:

Proposition 1.2: **A shift of resource endowments from generation 2 to generation 1 unambiguously increases welfare of generation 1 and reduces welfare of generation 2, and vice versa.**

<u>Proof:</u>

Since the resource stock is fully allocated as endowments, $R^e_2 = \beta\ (S_0\text{-}R^e_1)$. Substituting the price into demands and demands into utilities, welfare effects of changing resource endowments can be calculated. With $0 > z > 1$ and $S_0 \geq R^e_1$ the comparative static results are:

$$\frac{dU_1}{dR_1^e} = \frac{(1+\delta)(\alpha K_1^e + K_2^e)(1-z)}{(1-z)\alpha K_1^e R_1^e + (1-z)K_2^e R_1^e + \alpha K_1^e S_0 z} > 0 \qquad (7)$$

and

$$\frac{dU_2}{dR_1^e} = \frac{(1+\delta)(\alpha K_1^e + K_2^e)(z-1)}{(1-z)(S_0 - R_1^e)\alpha K_1^e + (S_0 - (1-z)R_1^e)K_2^e} < 0 \qquad (8)$$

■

From the comparison with a static general equilibrium model, proposition 1.2 should be fairly obvious. Propositions 1.1 and 1.2 together imply that for every possible distribution of resource endowments, there is a different resource depletion path. All of these depletion paths are efficient; however, they result in different welfare distributions between generations. Often, intertemporal efficiency is incorrectly taken as a sufficient condition for optimal resource depletion. However, an efficient depletion path is optimal only in an equilibrium that is based on the desired endowment distribution. The market mechanism only assures intertemporal efficiency. The market cannot make the decision on which generation should own how much of the resource. In the context of natural resources, this decision is particularly critical since it is irreversible (once an early generation has assumed ownership of the resource and consumed it, it cannot be consumed by later generations) and is imposed on later generations by the earlier generations. Following proposition 1.2, the first generation has an incentive to assume ownership of the full resource stock. Figure 1.2 (a) demonstrates the significance of the decision on who owns the resources by means of an example for a non-renewable resource (β = 1) with z = 0.5, α = 2, δ = 0.9, $K^e_1 = K^e_2 = 1$, and S_0 = 1. Utilities of generations 1 and 2 are plotted as a function of R^e_1.

The extent to which assumptions about which generations own the resource affect the welfare distribution depends on the relative importance of the resource in the economy. In this model, relative insignificance of the resource is measured by the parameter z that represents the expenditure share on the capital good K. Figure 1.2 (b) shows the utility of both generations as a function of z for $R^e_1 = S_0$ (with β = 1, α = 2, δ = 0.9, $K^e_1 = K^e_2$ = 1, and S_0 = 1). At one extreme, z = 0, K does not enter the utility function. Since generation 2 is endowed with K only, its endowment is worthless and its utility minus infinity. At the other extreme, z = 1, the resource is worthless and its distribution does not matter. Since trade cannot take place with only one good of value, and both generations are endowed with the same quantity of K, utility across generations is equal. As a result, the welfare relevance of resource endowments depends on the assumption about the relative importance of natural resources in the economy. As indicated in the introduction, this inquiry is motivated by the belief that natural capital depletion is widespread and that the relative importance of natural capital is higher than generally assumed if not only source but also sink resources, such as the environments capacity to absorb waste products, are taken into consideration.

To analyze the impacts of modifying the rate of reproduction of the natural resource, β, on welfare, the derivatives of equilibrium welfare with respect to β are evaluated:

$$\frac{dU_1}{d\beta} = \frac{\delta(1-z)}{\beta} > 0$$

$$\frac{dU_2}{d\beta} = \frac{(1+2d)(1-z)}{\beta} > 0 \tag{9}$$

Hence, an increase in the rate of resource reproduction unambiguously benefits both generations under any endowment distribution. This is not surprising since an increase in β increases the sum of resource endowments when S_0 is kept constant. Also, the impacts of the early generation's assumption about the ownership of the resource depend on the rate of reproduction of the resource, β. With increasing β, the endowment distribution required to achieve equal utility of both generations shifts toward the first generation. Figure 1.2 (c) depicts the utility profiles at $R^e_1 = 2/3 \cdot S_0$. Increased reproduction of the resource benefits generation 2 through a slower increase in resource prices as well as an increased endowment of the resource when R^e_1 is kept constant. This result highlights that distributional concerns are particularly important for non-renewable resources and renewable resources with a low rate of reproduction.

The possible impacts of varying the rate of return on capital investment are surprising at first. With the additional assumptions $R^e_1 = S_0$ (the first generation assumes ownership of the full resource stock) and $K^e_1 = K^e_2$, the welfare derivatives with respect to the rate of return, α, are:

$$\frac{dU_1}{d\alpha} > 0 \quad \textit{if} \quad \delta > \frac{1-z}{\alpha(2+\alpha-z)}$$

$$\frac{dU_2}{d\alpha} < 0 \quad \textit{if} \quad \begin{cases} \delta < \dfrac{\alpha(1-z)}{z+2\alpha z-\alpha} & \textit{if} \quad z > \dfrac{1}{1+2\alpha} \\ \delta > \dfrac{\alpha(1-z)}{z+2\alpha z-\alpha} & \textit{if} \quad z < \dfrac{1}{1+2\alpha} \end{cases} \tag{10}$$

Hence, the second generation's utility can fall with increasing productivity of capital. To see that the restrictions on the utility discount factor would be satisfied for a wide range of parameter values, consider the example of $\alpha = 2$ and $z = 0.5$. The comparative static

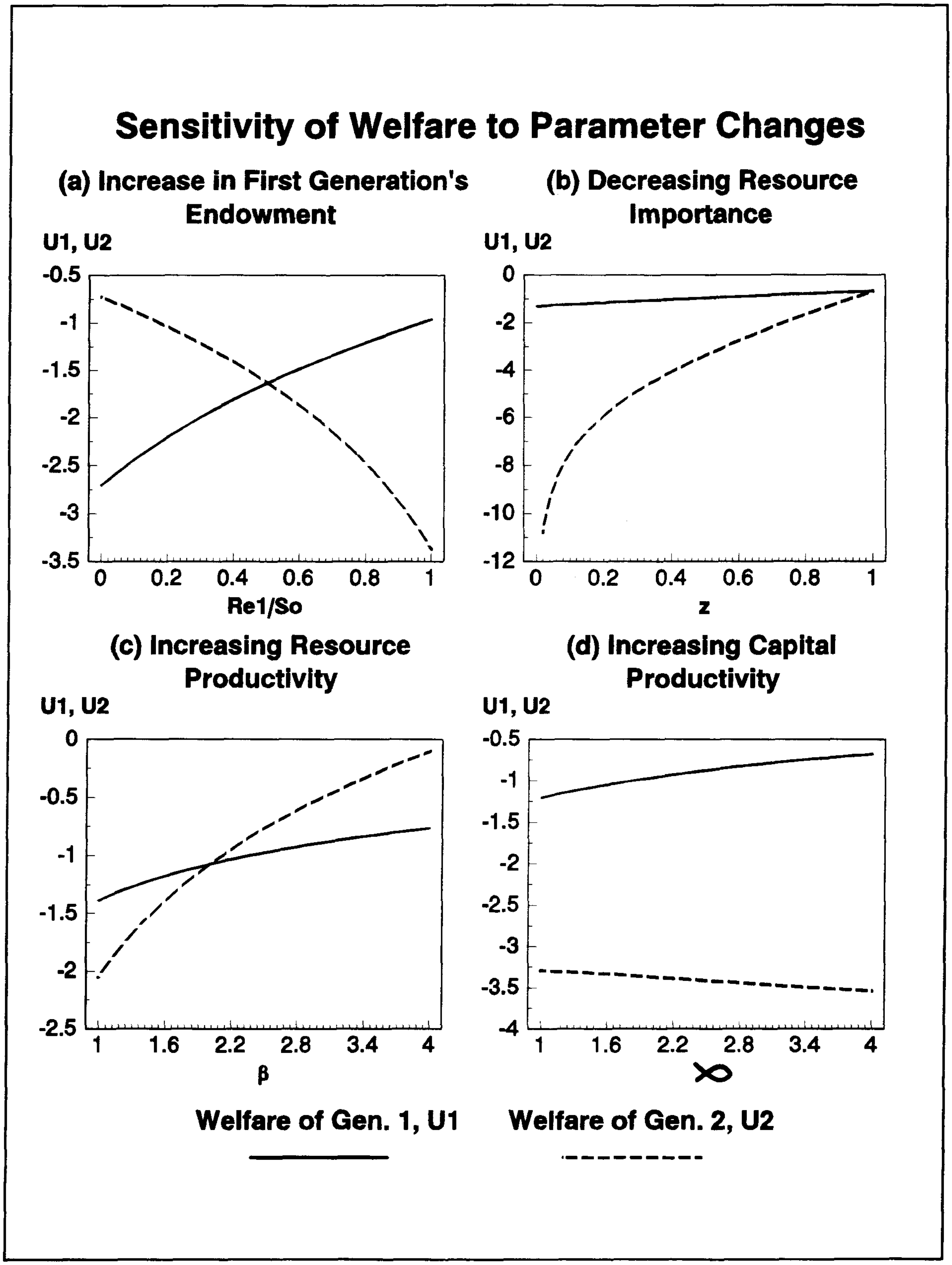

Figure 1.2 Sensitivity of Welfare to Parameter Changes

results in Equation (10) would then hold for any δ with $0.071 < \delta < 2$. A positive rate of pure time preference implies $\delta < 1$. Figure 1.2 (d) shows an example in which welfare of generation 2 declines with α ($\beta = 1$, $\delta = 0.9$, $K^e_1 = K^e_2 = 1$, and $S_0 = R^e_1 = 1$).

This result is important since it implies that if the early generation assumes ownership of a large share of the resource, technological progress that increases the rate of return on capital investment can make the second generation worse off. If generation 1 could choose α, for example through technological innovations, it would have an incentive to increase α at the expense of generation 2. The intuition as to why generation 2's welfare declines with increasing α is that generation 2 needs to buy the resource from generation 1 in exchange for capital. An increase in α increases the total amount of capital available and increases the resource price in terms of capital. This increase of the resource price increases the relative income of (the resource-owning) generation 1. Generation 1 would increase consumption of both goods and leave behind less of the natural resource. Unless the increased rate of return on generation 2's own capital endowment offsets the effect of an increased resource price (which, with most parameter values, is the case only at negative rates of time preference), generation 2 is made worse off. Clearly, this effect is limited to the specific type of technological progress that increases productivity of capital but does not change productivity of the natural resource. This effect appears to have practical relevance since the public good nature of many natural resources would lead to little incentives to invest in technological progress that would increase resource productivity. Hence, technological progress would often only increase the productivity of human-made capital, which would lead to increased resource depletion and reduced welfare of future generations.

Proposition 1.3: **An increase in the rate of reproduction of the natural resource, β, increases the welfare of both generations. Under the conditions in (10), with equal capital endowment of both generations and with all of the resource owned by generation 1, an increase in the rate of return on capital investment, α, increases welfare of generation 1 but reduces welfare of generation 2 and vice versa.**

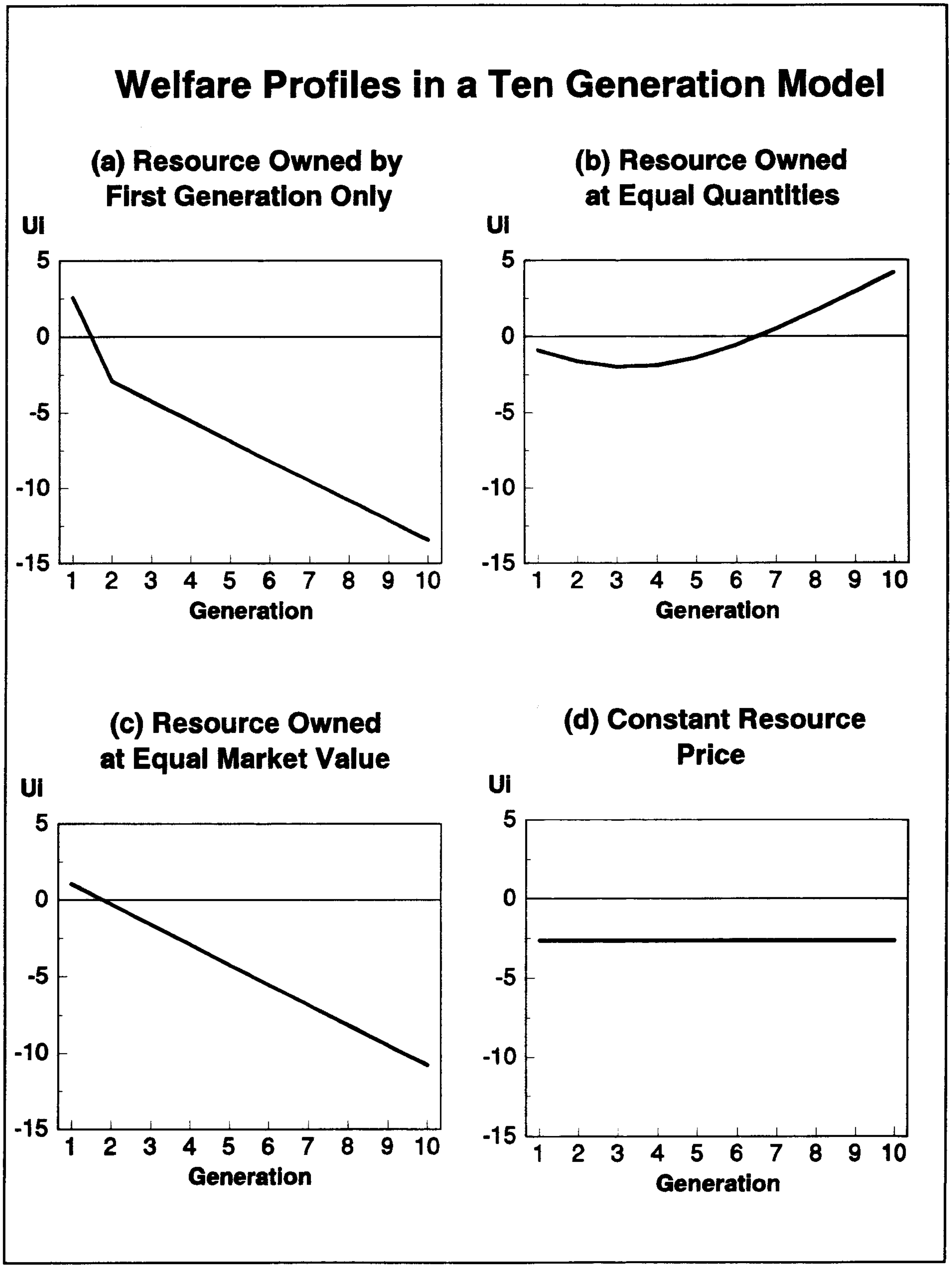

Figure 1.3 Welfare Profile with Ten Generations

Proof: Follows from equations (9) and (10). ■

The result that an increased return to capital investment can reduce the welfare of generation 2 is related to other models that show how imbalanced technological progress can hurt agents through price effects. In the international trade literature such a terms of trade effects has become known as immiserizing growth (see Bhagwati 1958 and 1968). Immiserizing growth occurs when technological progress in the export sector leads to a worsening of the terms of trade such that the negative price effect exceeds the positive effect from an increased quantity of the exported good. Similarly, in the above model, an increase of the capital good, which is "exported" by generation 2, leads to a decrease of its market price that can more than offset the positive quantity effect. Corresponding to the conditions giving rise to immiserizing growth, the negative welfare effect for generation 2 depends on this generation's competitive behaviour despite its market power for the capital good.

2.1.3 An Example With Ten Generations

In order to gain an intuitive understanding of the endowment effect with more than two generations, a numerical example with ten generations is presented in this subsection. Throughout the example, an interior solution is assumed. The example is based on $z = 0.5$, $\beta = 1$, $\delta = 0.9$ and $K^e_i = 1$ (for all ten generations). Figure 1.3 (a), (b), and (c) depict the utility profiles across generations with different distributions of the initial resource stock of 10 and $\alpha = 2$. Figure 1.3 (a) shows the utility profile when all 10 units of the resource are allocated to the first generation. Hence, generation 1 has a higher valued endowment while the market value of the endowment of generations 2-10 is equal. The declining utility from generations 2 to 10 stems from the increasing resource price (following the Hotelling path). Figure 1.3 (b) shows the utility profile resulting from distribution of the resource in equal quantities to all ten generations ($R^e_i = 1$). The U-shaped utility profile results from the interaction between the income effect (higher market value of later generations' endowments) and the price effect. Figure 1.3 (c) shows the isolated price effect. This case is based on a distribution in which the market value of resource endowments has been equalized across all ten generations by distributing the resource in inverse proportions to the current resource price. With equal endowment value for every generation no trade occurs since the ratio between the market value of both goods' endowments is equal. Utility decreases strictly due to the price effect. Figure 1.3 (d), finally, reflects a constant resource price (achieved by assuming $\alpha = 1$) and equal resource distribution, resulting in no trade and equal utility among all generations.

2.1.4 A Two-Generation Model With Production

For the consumption model in the preceding section, a very simple structure was deliberately chosen in order to be able to derive simple equilibria for cases with many generations. Some features of the model, however, are excessively simplistic. In particular, it could be suspected that the welfare results would be weakened in a model that allows the use of the resource not only as a consumption good but also as an input to production. Intuitively, one might argue that if the resource can be made productive, its ownership and use by earlier generations may actually benefit later generations as well. Hence, it would be important to verify the robustness of some of the previous results in a model that would include production of a consumption good, using resources and capital as input, with an endogenous rate of return. This section examines a two-generation model that incorporates these features.

There are two goods in the economy, the investment and consumption good, K, and a non-renewable resource, R. Output of K is produced from K and R with a log production function:

$$f_i[R_i^n, K_i^n] = I\,Log[1 + K_i^n] + Log[1 + R_i^n] \tag{11}$$

where f_i is output of K at time $t = i+1$ and K^n_t and R^n_t are inputs of capital and the natural resource, respectively, at time $t = i$. There are only 2 generations. Generation 1 lives at times 1 and 2 and generation 2 at times 2 and 3. Generation i receives the endowment (K^e_i, R^e_i) at time $t = i$ (the early time of its life). For simplicity, generation i consumes only K and only at time t = i+1 (the late time of its life). The parameter I in the production function is chosen such that the marginal rate of return on investment of K always exceeds 1. Hence, K is always invested and never stored. At time 2, generations 1 and 2 can trade R for K at price p (K is the numeraire good). Both generations behave competitively. Generations maximize their consumption by choice of the amounts traded (generation 1 sells R^s_1 of the resource; generation 2 buys R^b_2 of the resource) subject to their respective budget constraints. Since both generations consume only one good at one point in time, there is no need to define a utility function. Given the endowments, the trade choices determine investments. There is no uncertainty and generations have perfect foresight.

The maximization problem of generation 1 is:

$$\max_{R_1^s} \ C_1 = I Log[1+K_1^e] + Log[1+R_1^e - R_1^s] + pR_1^s \tag{12}$$

Generation 2's problem is:

$$\max_{R_2^b} \ C_2 = I Log[1+K_2^e - pR_2^b] + Log[1+R_2^e + R_2^b] \tag{13}$$

The resulting trade choices are:

$$R_1^s = 1 - \frac{1}{p} + R_1^e \qquad R_2^b = \frac{1+K_2^e - Ip(1+R_2^e)}{p(1+I)} \tag{14}$$

The equilibrium price can be obtained from the market clearing condition $R^s_1 = R^b_2$:

$$p = \frac{K_2^e + I + 2}{1 + R_1^e + I(2 + R_1^e + R_2^e)} \tag{15}$$

With $R^e_2 = R^e_1 - S_0$, the resulting equilibrium consumptions of both generations are:

$$C_1 = \frac{1 - I + K_2^e - IS_0 + R_1^e(1 + I + K_2^e)}{1 + 2I + IS_0 + R_1^e} + I Log[1 + K_1^e] + Log\left[\frac{1 + 2I + IS_0 + R_1^e}{2 + I + K_2^e}\right]$$

$$C_2 = Log\left[\frac{3 + K_2^e(2 + S_0) + 2S_0 - R_1^e}{2 + I + K_2^e}\right] + I Log\left[\frac{I(3 + K_2^e(2 + S_0) + 2S_0 - R_1^e)}{1 + I(2 + S_0) + R_1^e}\right] \quad \textbf{(16)}$$

Proposition 1.4: **In the two-generation production economy, a shift of resource endowment toward generation 1 increases consumption of generation 1 and decreases consumption of generation 2. Also, the price of the resource depends on the distribution of resource endowments between generations. The price decreases with increasing distribution of the resource toward generation 1.**

Proof:

With $R^e_2 = R^e_1 - S_0$ and $R^e_1 \le S_0$, the comparative statics results confirm the results for the consumption economy that welfare of generation 1 increases and welfare of generation 2 decreases with increased distribution of resource endowment toward generation 1:

$$\frac{dC_1}{dR_1^e} = \frac{I^2(2 + S_0) + I(6 + 2K_2^e + 3S_0 + K_2^e S_0) + 1 + R_1^e}{(1 + R_1^e + I(2 + S_0))^2} > 0$$

$$\frac{dC_2}{dR_1^e} = \frac{I^2(2 + S_0) + I(6 + 2K_2^e + 3S_0 + K_2^e S_0) + 1 + R_1^e}{-(1 + R_1^e + I(2 + S_0))(3 + 2K_2^e + S_0(2 + K_2^e) - R_1^e)} < 0 \quad \textbf{(17)}$$

Also, in this model, the resource price, p, depends on resource endowment distribution:

$$\frac{dp}{dR_1^e} = -\frac{2 + I + K_2^e}{(1 + R_1^e + I(2 + S_0))^2} < 0 \quad \textbf{(18)}$$

■

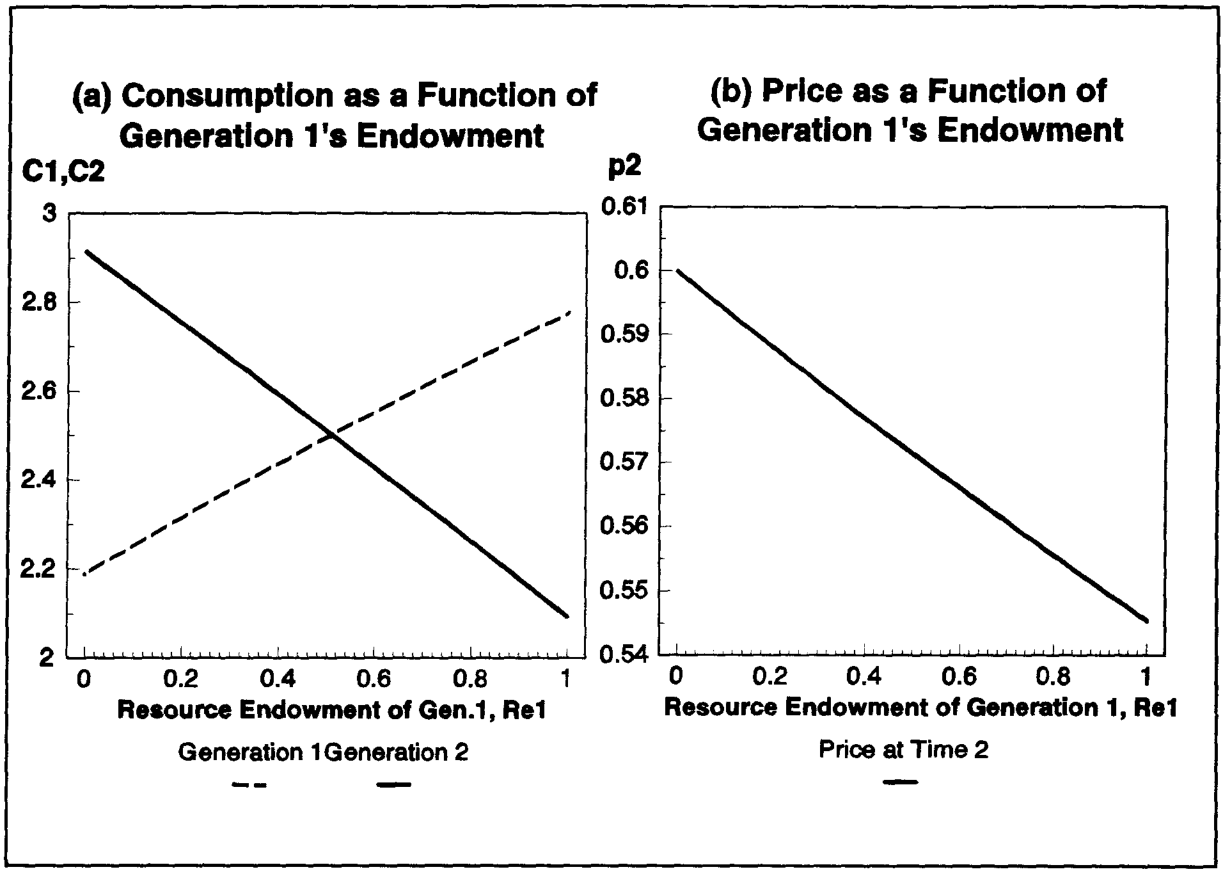

Figure 1.4 Equilibrium Changes with Increases in Generation 1's Endowment

These impacts of increasing resource distribution to generation 1 are depicted in Figure 1.4 for a numerical example with $K^c_1 = K^c_2 = 1$, $S_0 = 1$, and $I = 3$. The model, analyzed in this section for two generations, can also be solved for three and more generations. The main results of the discussed consumption model hold then as well. In addition, it can be shown that with three or more generations, the discount rate (the rate at which the resource price rises) decreases with increased distribution of resource endowments toward earlier generations. Since the discount rate rises with changes of the resource distribution toward the earlier generation, there is an additional bias in such distribution that was not apparent in an economy with a constant rate of return on capital investment. In addition to the income effect from a lesser endowment of generation 2, there is the discount rate effect that leads to a faster rise in the resource price, benefiting earlier generations. In addition to the log-production function, other similar models were analyzed; but the results are not reported here in detail. For example, with a Cobb-Douglas production function, the model can be solved for two generations with the main results being the same.

2.2 The Channelling Effect

In an intergenerational world, not all generations can trade with each other directly. Generations, far apart in time, can trade with each other only indirectly through the channel of intermediate generations. Specifically, the volume of trade between distant generation is limited by the wealth of intermediate generations since an intermediate generation's ability to buy goods from an early generation and sell them to a later generation is restricted by its own wealth. This section seeks to explore the implications of this channelling effect. First, consider the general consumption model introduced in section 2.1.1. In a two-generation model, all generations overlap and can trade with each other directly. A three-generation model is the simplest one possible to explore the impacts of missing markets between non-adjacent generations since generations 1 and 3 would not overlap and could not trade with each other directly.

Proposition 1.1 has already established that efficient resource depletion is achieved if the N generation equilibrium implies strictly positive investment of K and R of all generations. Hence, the interesting aspects of a three-generation model are its corner solutions. The case of $R^i_2 = 0$ will be discussed later. The discussion here focusses on the corner solution with $K^i_2 = 0$; hence, the intermediate generation invests only in resources and not capital. This case would occur if most of the resource is owned by generation 1, and generation 2 has to buy resources from generation 1 at time 2 in order to sell it to generation 3 at time 3. Capital investment of generation 2 at time t = 2 can be expressed as:

$$K_2^i = \alpha(K_1^e - K_{1,1}^c) + K_2^e - K_{1,2}^c - K_{2,2}^c \qquad (19)$$

After demands and prices are substituted into equation (19), the conditions can be determined under which this corner solution ($K^i_2 \leq 0$) will be obtained (with $z = 0.5$, $\beta = 1$ and $R^e_1 = S_0$):

$$K_2^i \begin{cases} > 0 & if \quad K_2^e > \dfrac{1+\delta}{\alpha\,\delta} K_3^e \\ = 0 & if \quad K_2^e \leq \dfrac{1+\delta}{\alpha\,\delta} K_3^e \end{cases} \tag{20}$$

As expected, the corner solution arises if generation 2 is 'poor' compared to generation 3. The equilibrium for this corner solution is derived in Appendix I-B. Demands of generation 1 and 3 remain as in equation (6). The demands of generation 2 and the prices, however, change.

Proposition 1.5: **If, in equilibrium, generation 2 does not undertake capital investment, the resource price changes with the distribution of resource endowments between generations In particular, a shift of endowment (from generations 2 and 3, equally) to generation 1 leads to a decrease in p_2 and an increase in p_3.**

Proof:

In case of the corner solution, prices are (from Appendix I-B):

$$p_2 = \frac{(1+\delta)\,\alpha\,K_1^e + (1+2\,\delta)\,K_2^e}{(1+\delta)\,R_1^e + R_2^e}$$

$$p_3 = \frac{((1+\delta)\,\alpha\,K_1^e + (1+2\,\delta)\,K_2^e)\,K_3^e}{\delta\,K_2^e R_1^e + \alpha\,\delta\,K_1^e R_2^e + 2\,\delta\,K_2^e R_2^e + (1+\delta)\,\alpha\,K_1^e R_3^e + (1+2\,\delta)\,K_2^e R_3^e} \tag{21}$$

These prices depend on the resource distribution. Setting $R^e_2 = R^e_3 = (S_0 - R^e_1)/2$, the price effects of shifting the resource endowment toward generation 1 can be assessed:

$$\frac{dp_2}{dR_1^e} = \frac{-2(1+2\delta)((1+\delta)K_1^e + (1+2\delta)K_1^e)}{((1+2\delta)R_1^e + S_0)^2} < 0$$

$$\frac{dp_3}{dR_1^e} = \frac{2(1+2\delta)(\alpha K_1^e + K_2^e)((1+\delta)K_1^e + (1+2\delta)K_2^e)K_3^e}{((1+2\delta)(-K_1^e R_1^e - K_2^e R_1^e + K_1^e S_0) + (1+4\delta)K_2^e S_0)^2} > 0 \tag{22}$$

■

The corner solution arises when most of the resource is owned by generation 1 because generation 2 has to be sufficiently wealthy to buy the resource from generation 1 and sell it to generation 3. Positive investment by generation 2 ($K^i_2 > 0$) requires the capital endowment of the second generation to exceed an amount proportional to the third generation's capital endowment. If the intermediate generation's endowment is insufficient, investment is zero and the Hotelling price path for the resource will no longer hold between times 2 to 3. The price of the resource rises faster than the rate of return on capital investment. Normally, this would induce generation 2 to purchase more of the resource from generation 1 and sell it to generation 3. However, generation 2 can offer generation 1 at most K^e_2 for acquiring the natural resource demanded by generations 2 and 3, regardless of generation 3's wealth. Note that this channelling effect is not due to myopia of generation 2 or some market failure. It is the result of the corner solution in which generation 2 already spends all its endowment on buying the resource from generation 1 (beside own consumption at time 2). Since the wealth of the intermediate generations is a technical constraint in the model, the corner solution equilibrium is not inefficient. A Pareto improvement could only be achieved if later generations were able to transfer capital (discounted at the rate of return) to intermediate generations. This would be technically infeasible if K^e is thought of as an endowment that is not physically present before its owner-generation is born (i.e. labour endowment). Even though it does not imply an inefficiency, the result emphasizes the distributional concerns about the first generation's ownership of the resource stock since future generations' access to the resource would be limited not only by their own wealth but also by the wealth of intermediate generations. The channelling effect implies that the impact that the demand of distant generations can have on current markets is limited by the intermediate generations' wealth.

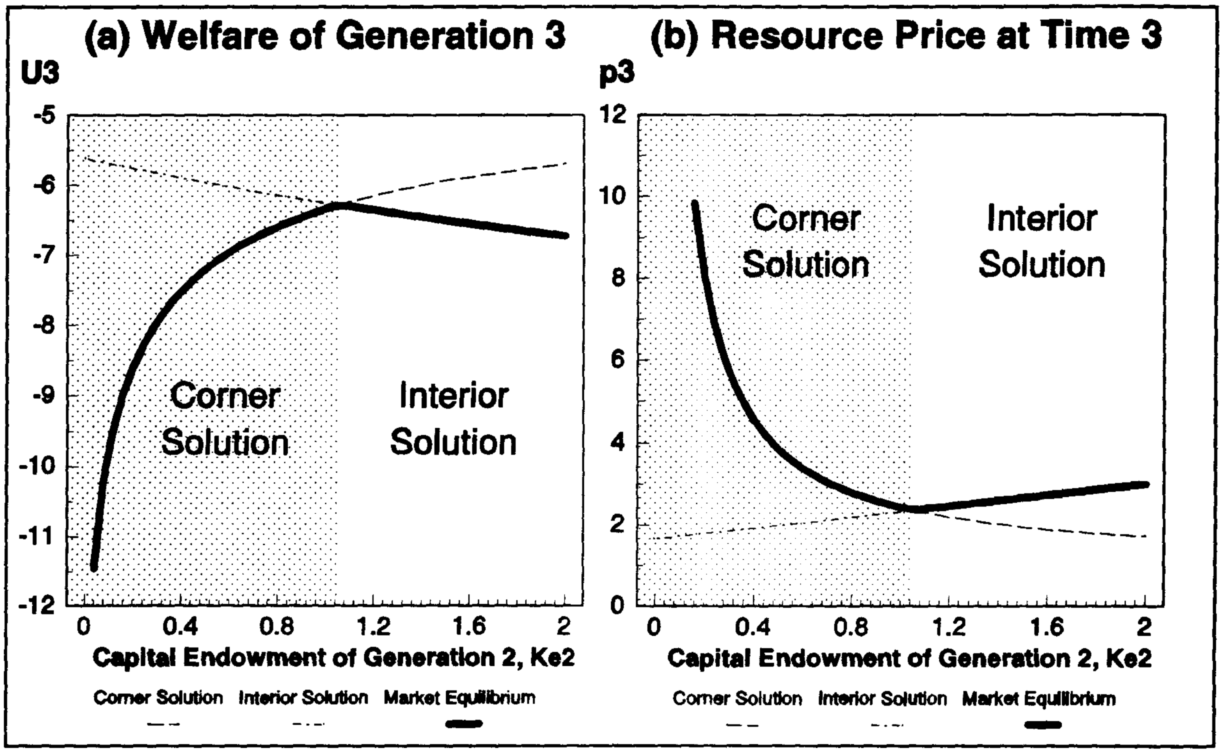

Figure 1.5 The Channelling Effect

Figure 1.5 depicts a numerical example ($K^e_1 = 1$, $K^e_3 = 1$, $S_0 = R^e_1 = 3$, $\delta = 0.9$, $\alpha = 2$) for the impact of the wealth of generation 2 on the resource price at time 3 and the utility of generation 3. At these parameter values, the corner solution is obtained at any $K^e_2 < 1.055$. Hence, the market equilibrium for $K^e_2 > 1.055$ corresponds to the interior solution while, for $K^e_2 < 1.055$, it corresponds to the corner solution. In case of an interior solution, increasing the wealth of generation 2 bids up the price of the resource for all generations, leading to declining utility of generation 3, whose endowment value remains unchanged. In case of a corner solution, the amount of the resource offered to generation 3 is constrained by K^e_2 and the resource price at time 3 rises as K^e_2 is lowered with adverse welfare impacts for generation 3. The resource price has its minimum and utility of generation 3 its maximum at $K^e_2 = 1.055$. The practical relevance of the channelling effect is highlighted by the fact that the corner solution is obtained for a wide range of reasonable parameter values. In the numerical example above, the channelling effect prevails already for equal capital endowments of all generations ($K^e_i = 1$).

As the number of generations in the model is increased, the channelling effect becomes more severe since intermediate generations have to channel the resource not only to one but to all future generations. The wealth of intermediate generations limits the amount by which all future generations together can effectively bid on resources in the present. Now, consider the extent to which the channelling effect limits the amount of resources that will be left behind for all future generations if the first generation assumes ownership of the full resource stock in an N-generation model.

Proposition 1.6: **Since non-adjacent generations can trade with each other only through the channel of adjacent generations, the amount by which future generations' demand can be effective on resource markets before their lifetimes, is limited by intermediate generations' wealth. If the first generation assumes ownership of the full stock of a non-renewable resource, the total amount of the resource that can be obtained by any number of future generations will be limited to a fraction of the resource stock that is determined by the capital endowment of generations 1 and 2 only.**

Proof:

The payment that generation 1 receives from generation 2 for resources sold for the use of all future generations cannot exceed the total capital endowment of generation 2, hence:

$$p_2(S_0 - R^c_{1,1} - R^c_{1,2}) \leq K^e_2 \qquad \textbf{(23)}$$

Substituting the demands of generation 1 (from Equation (38) in Appendix I-A) into this equation, it can be solved for p_2:

$$p_2 \leq \frac{\alpha K_1^e + 2K_2^e}{S_0} \tag{24}$$

Substituting p_2 back into demands of generation 1 yields:

$$R_{1,1}^c + R_{1,2}^c \geq \frac{\alpha K_1^e + K_2^e}{\alpha K_1^e + 2K_2^e} S_0 \tag{25}$$

The resource consumption of all future generations is, hence, bounded from above as a fraction of initial resource stock that is determined by the wealth of the first two generations only:

$$\sum_{i=2}^{N} R_{i,i}^c + R_{i,i+1}^c \leq \left(1 - \frac{\alpha K_1^e + K_2^e}{\alpha K_1^e + 2K_2^e}\right) S_0 \tag{26}$$

For example, with $K^e_1 = K^e_2 = 1$ and $\alpha = 2$, the first generation will consume at least 3/4 of the resource stock while all future generations together will consume at most 1/4 of the resource stock. ■

Models, different from the one above, can be constructed that would avoid the channelling effect. However, the effect is of relevance even if some of the assumptions made above are relaxed. The channelling effect occurs as well if the production model in section 2.1.4 is extended to three or more generations. In principle, the channelling effect remains in effect even in a more realistic setting with more than two generations overlapping at any one time. Suppose, the first x generations own the resource stock. There are y more generations that overlap with at least one of the first x generations. Then, the amount of the resource that would be available to all future generations $(x+1,\ldots,\infty)$ is always less or equal to the amount of the resource that generations 1 to x are willing to sell against payment of generations' $x+1$ to $x+y$ aggregate endowment and is independent of the wealth of any later generation $(x+y+1,\ldots,\infty)$.

The channelling effect makes transparent the way in which future generations are excluded from current resource markets. It increases the concerns about intergenerational equity if early generations assume ownership of the resource stock. Also, it shows that if early generations want to benefit future generations, they have to do so in a way that benefits all generations. For example, predictable catastrophic events that directly affect only one generation could, in fact, drastically reduce welfare of all subsequent generations, since it would lead to excessive resource depletion by the generations before the one impoverished generation. Moreover, the channelling effect shows the limited value of resource prices as an indicator of long-term resource scarcity. It would be consistent with this model to observe a period of resource abundance and low resource prices over several generations followed by generations with drastic resource price increases, resource scarcity and declining welfare.

It appears plausible that the channelling effect has real life relevance, particularly for developing countries that face a constraint on foreign exchange borrowing. The resource owning (old) generation would rapidly deplete the country's natural resources since the young generation is poor and unable to borrow internationally in order to buy the resource and later sell it to the next (richer) generation. Hence, the channelling effect would be particularly severe in currently poor countries with high long-term growth expectations. If environmental amenities are considered a luxury good whose expenditure share rises with increasing income, the effect would be exacerbated. Countries like Brazil or Indonesia with rapid depletion of their natural capital would be candidates for an emprical investigation whether they are in a channelling situation. Note that the frictions in international capital markets (for example a country's foreign borrowing constraint) bring about a real market inefficiency that, through the channelling effect, leads to excessive depletion of natural resources.

3 Natural Resource Depletion and Intergenerational Compensation

The discussion in section 2 has shown that the efficiency of resource markets alone does not guarantee an optimal allocation of resources to different generations. Therefore, it is important to consider the instruments that could be used to achieve such an optimal resource allocation. In this section, different institutional arrangements for implementing a desired welfare distribution between generations are discussed. The modeling approach in section 2 would suggest the explicit assignment of resource endowments to different generation. This approach was taken by Howarth and Norgaard (1990). Inefficiencies that can result from using this approach will be discussed. An alternative approach would be explicit compensation of future generations for resource depletion. This was suggested by Hartwick (1977). Two different approaches for implementing Hartwick's suggestion are discussed in this section.

3.1 Efficiency Limits of Intergenerational Resource Endowments

Howarth and Norgaard (1990) suggest that the optimal, as opposed to merely efficient, allocation of resources can be arrived at by maximizing a social welfare function by choice of intergenerational resource endowments. They solve their two-generation model for the optimal resource endowments under a maximin and an additive intergenerational welfare function. However, it can be shown that this approach can lead to inefficiencies in a model with more than two generations. Consider the three generation model discussed in section 2.2. If resource endowments are distributed primarily toward generation 3, a situation can arise in which the demand for the resource at times 1 and 2 exceeds the resource endowments of generations 1 and 2. In this case, generation 2 would want to buy resources from generation 3 at time 3 but use it already at time 2 (i.e. invest a negative amount of the resource). However, resource investment are required to be non-negative and a corner solution with zero resource investment would arise. This corner solution with zero resource investment is the opposite of the previously discussed corner solution with zero capital investment that gives rise to the channelling effect.

If generation 2's optimal resource investment declines to zero, and the corner solution arises, the Hotelling price path would be violated by the resource price rising at less than the rate of return on capital investment, α. Such an equilibrium would be inefficient since, if the resource is assumed to be physically existent already before its owner-generation is born, there exists a feasible redistribution of endowments that could lead to an actual Pareto improvement. Specifically, in a three-generation model zero resource investment by generation 2 would lead to $p_3 < \alpha p_2$. Then, a feasible redistribution of resource endowments would involve shifting a marginal share of generation 3's resource endowment, ΔR, to generation 2. The marginal loss for generation 3 would be $p_3 \Delta R$. At time 2, generation 2 could provide capital investment of $p_2 \Delta R$ as compensation for generation 3 and be indifferent at the margin. Generation 3 would receive $\alpha p_2 \Delta R$ from this investment and would be made strictly better off since $\alpha p_2 > p_3$. Hence an actual Pareto improvement would be achieved. Thus, the initial resource distribution leads to an inefficiency that is caused by incomplete markets. The market incompleteness consists of generation 3's inability to trade its resource endowments before time 3. Since generation 3 cannot trade before time 3, the endowment of generation 3 can never be consumed before time 3, even if trade could increase the welfare of all generations.

Numerical analysis shows that this corner solution arises in a model with more than three generations for a variety of parameter values with equal capital endowments if resource endowments are chosen to equalize utility across generations. In these cases, future generations are given ownership over a share of the resources for distributional reasons. However, for efficiency reasons, earlier generations should be able to use the resource and hence, need to be able to buy the resource from later generations. Since they cannot directly trade with non-adjacent generations, an inefficiency arises. Subsequently, a desired intergenerational welfare distribution may not be achievable through efficient redistribution of resource endowments. Hence, it would be desirable to find an alternative mechanism by which the desired intergenerational welfare distribution could be achieved efficiently. Such a mechanism, in which a resource consuming generation would explicitly compensate future generations for resource depletion with capital investment, will be discussed in the next subsection.

3.2 Compensation with Hartwick's Rule

Above, I have shown that a desired intergenerational welfare distribution may not be achievable through an efficient redistribution of resource endowments. In this subsection, I will analyze the possibility to achieve the desired intergenerational welfare distribution through a direct compensation mechanism. In this subsection it is assumed that the desired intergenerational welfare distribution is determined by a maximin welfare function (hence, a social planner would maximize the welfare of the worst-off generation). The use of a maximin welfare function does not mean to imply a normative statement. However, this particular welfare function is chosen since it focusses the analysis on intergenerational welfare distribution.

Hartwick (1977) shows in a continuous time model with Cobb-Douglas production that welfare is constant across time if, first, the resource is priced competitively (the price increases at the rate of interest, and the resource depletes asymptotically), and second, net capital investments equal competitive resource profits. Zero-population growth is an additional assumption of the model. Dixit, Hammond and Hoel (1980) have obtained the same result with general functional forms and showed the conditions under which the constant welfare path is the maximin welfare path. The investing of competitive resource profits will be called Hartwick's rule (HR). The intuition of Hartwick's rule is that if competitive resource profits are invested in perpetuity and only returns to this investment are consumed, the returns to this investment would increase with time and compensate, in welfare terms, precisely for the rising resource price. Hartwick (1977) and Dixit, Hammond and Hoel (1980) present Hartwick's rule as an investment rule that leads to constant welfare. However, use of the rule is not modeled in an explicitly intergenerational framework. They do not discuss conditions that would lead to investment according to Hartwick's rule in a competitive economy. Also, they do not discuss institutional arrangements that could be used to implement Hartwick's rule. These questions will be discussed throughout the remainder of this chapter.

Hartwick's rule could be implemented in a socially managed economy by determining consumption and investment plans that follow Hartwick's rule. The following analysis is motivated by the belief that a socially managed economy may not be desirable. Therefore, it is important to know which interventions would be necessary for implementation of Hartwick's rule in a decentralized, competitive economy. In a competitive model of identical and selfish generations with positive marginal utility of consumption, Hartwick's rule could not be realized since generations would always consume or sell their capital stock, but never bequeath it to the next generation. Two different interventions for implementing Hartwick's rule will be discussed. Section 3.2.1 suggests a mechanism based on public resource ownership. Section 3.2.2 discusses the implementation of Hartwick's rule with private resource ownership. The latter discussion is also applicable to a situation in which generations are not selfish and voluntarily bequeath some capital to their successors.

3.2.1 Compensation with Public Resource Ownership

In this section, I will apply Hartwick's rule to an intergenerational context and suggest a mechanism that would lead to net-zero investment (change in capital stock minus resource depletion), satisfying Hartwick's rule. No single generation would own the resource. Instead, every generation would have the right to buy the resource against a payment that is invested in perpetuity. The price at which every generation can buy the resource is administered such that it follows the Hotelling path and leads to asymptotical depletion of the resource. Hence, the resource is allocated efficiently and trade between generation would not take place. (Simultaneously living generations could buy the resource at the same price. Since the Hotelling price path is administered, there are no arbitrage profits that could be made through trade.) The instantaneous returns to accumulating compensatory investment are added to the current generation's endowment. Following Hartwick's rule, a constant welfare path would be obtained if net investment at all times equalled resource profits. Since all resource profits are invested by the suggested mechanism, no additional investment or borrowing may take place in the economy for Hartwick's rule to hold. No additional investment would be undertaken if either each generation's lifetime was infinitely short, or all individual generations' optimal savings were zero, or net investment at all times was zero because saving and dissaving of overlapping generations cancel out perfectly at any time. Under any one of these three conditions, the constant welfare path is obtained through administration of the efficient price path. The following model will formally show how such an institutional arrangement would bring about a constant welfare path.

The model is similar in structure to the consumption model in the first section of this chapter. However, Dasgupta and Mitra (1983) have shown that Hartwick's rule is incompatible with competitive pricing in a discrete time model. A continuous time model would be closer to the realities of intergenerational trade and resource depletion. Since it would be unwise to use a modeling abstraction which is known to distort the results in this context, a continuous time model is used. Under the suggested pricing mechanism, there are no trade opportunities between generations. Hence, for simplicity, the generations in this model do not actually overlap but simply replace each other. As before, there are two consumption goods, a non-perishable, non-renewable resource, R, with the initial stock, S_0, and capital, K. The initial capital stock is zero and the instantaneous return to invested capital is α. There is an infinite number of generations $i = 0,1,2,\ldots,\infty$. Generation i lives in the time interval $[i,i+1]$. The consumption streams are denoted $k^c(t)$ and $r^c(t)$. Since only one generation lives at any time, t identifies time as well as the currently living generation. Generation i receives constant instantaneous endowments at the rate k^e_i. This endowment consists on the original endowment for all generations, k^e_0, and returns to compensating investment accumulated by all previous generations. Hence:

$$k_i^e = k_0^e + \alpha \int_0^i p(t) r^c(t)\, dt \tag{27}$$

Generation i's utility function is:

$$U_i = \int_i^{i+1} e^{-\delta(t-i)} \big(z Log[k^c(t)] + (1-z) Log[r^c(t)] \big) dt \tag{28}$$

where δ is the instantaneous utility discount rate. Generation i maximizes its utility by choice of consumption, $k^c(t)$ and $r^c(t)$, subject to the budget constraint:

$$\dot{X}(t) = k_i^e + \alpha (X(t) + C(t)) - k^c(t) - p(t) r^c(t) \tag{29}$$

where X(t) is the stock of investments of generation i's own capital (with i = Integer[t]). The initial and terminal conditions for X(t) are X(i) = 0 and X(i+1) = 0. C(t) is compensatory investment accumulated during the lifetime of this generation i, with:

$$C(t) = \int_{Integer(t)}^{t} p(t) r^c(t)\, dt \tag{30}$$

A generation receives the instantaneous returns to accumulating compensatory investment, αC(t), as an addition to their endowment. This is reflected in their budget constraint, (29). They do not treat C(t) as a function of their choice variable $r^c(t)$. This reflects the assumption of competitive resource depletion which is a component of Hartwick's rule. To find the demands, the maximization problem is solved for the optimal consumption streams using the Hamiltonian approach (for an exposition of the Hamiltonian approach to continuous time optimization see, for example, Conrad and Clark 1987). The Hamiltonian is:

$$H = e^{-\delta(t-i)} \Big[z Log[k^c(t)] + (1-z) Log[r^c(t)] + \lambda(t) \Big(k_i^e - k^c(t) - p(t) r^c(t) + \alpha (X(t) + C(t)) \Big) \Big] \tag{31}$$

The first order conditions are:

$$\frac{dH}{dk^c(t)} = 0 \qquad \frac{dH}{dr^c(t)} = 0 \qquad \dot{\lambda}(t) = -\frac{dH}{dX(t)} \qquad \dot{X}(t) = \frac{dH}{d\lambda(t)} \tag{32}$$

With the border conditions X(i) = 0 and X(i+1) = 0, the system of first order conditions can be solved for the demands:

$$k^c(t) = \frac{e^{(\alpha-\delta)(t-i)} z k_i^e}{q}, \quad r^c(t) = \frac{e^{(\alpha-\delta)(t-i)}(1-z)k_i^e}{q\ p(t)}$$
$$\text{with} \quad q = \frac{\alpha(-\delta e^{\alpha} + \delta e^{\delta} + \alpha e^{\alpha} z - \delta e^{\delta} z - \alpha e^{\alpha+\delta} z + \delta e^{\alpha+\delta} z)}{\delta(\delta-\alpha)(e^{\alpha+\delta} - e^{\delta})} \tag{33}$$

In order to fulfil Hartwick's rule, investment in addition to compensatory investment for resource depletion must be zero at all times (X(t) = 0). With X(t) = 0, instantaneous utility within one generation would be constant. Substituting demands into utility and setting the derivative of instantaneous utility with respect to time equal to zero, gives $\delta = \alpha z$ (the utility discount rate equals the rate of reproduction of goods weighted by their expenditure share). This is a restriction on the utility function that will be imposed as an assumption about preferences, in order to ensures constant instantaneous utility within each generation. The significance of this assumption will be explored below. Now, the model can be used to show the following:

Proposition 1.7: **With $\delta = \alpha z$ and an administered resource price, p, rising at the rate α such that the resource depletes asymptotically, constant welfare across generations will be obtained by selling the resource to any generation at the administered price, investing the proceeds in perpetuity and returning the instantaneous returns to this compensatory investment to the currently living generation as augmentation of their endowment.**

Proof:

Substituting $\delta = \alpha z$ into equation (33) gives q = 1. Since every generations' instantaneous utility is constant within their lifetimes, it is sufficient to compare instantaneous utility of generations i at t = i with instantaneous utility of generation i+1 at t = i+1. The resource price is administered as the Hotelling price path: $p(t) = p(0)\, e^{\alpha t}$. Substituting resource demand (33) into (27) leads to the following relation between endowments of consecutive generations:

$$k^{e}_{i+1} = k^{e}_{i}\, e^{\alpha - \alpha z} \tag{34}$$

Also with $p(i+1) = e^{\alpha}\, p(i)$, $r^{c}(i+1) = r^{c}(i)\, e^{-\alpha z}$. Denoting instantaneous utility of generation i+1, u(i+1):

$$\begin{aligned} u(i+1) &= z Log[k^{c}(i+1)] + (1-z) Log[r^{c}(i+1)] \\ &= z Log[k^{c}(i)\, e^{\alpha - \alpha z}] + (1-z) Log[r^{c}(i)\, e^{-\alpha z}] \\ &= z Log[k^{c}(i)] + \alpha z - z^{2}\alpha + (1-z) Log[r^{c}(i)] + z^{2}\alpha - \alpha z \\ &= z Log[k^{c}(i)] + (1-z) Log[r^{c}(i)] \\ &= u(i) \end{aligned} \tag{35}$$

With $\delta = \alpha z$, instantaneous utility within any one generation is constant; equation (35) shows that instantaneous utilities at t = i and t = i+1 are equal across generations; hence, utility is constant across generations i and i+1, and hence across all generations. Therefore, administration of the Hotelling price path, at which the resource does not deplete in finite time, is sufficient to obtain constant utility across generations. ■

It turns out that, with $\delta = \alpha z$, $k^{c}(t)$ and $r^{c}(t)$ are continuous across generations. The administration of p(t) leads to the same price, consumption and instantaneous utility paths that would be obtained through competitive markets with only one infinitely living generation. With $\delta = \alpha z$, p(0) is easily calculated from $r^{c}(t) = k^{e}_{0}(1-z)/(e^{\alpha z t}p(0))$ by equating resource consumption until infinity with the initial resource stock S_0 at the time at which accumulation of compensatory investment begins:

$$S_0 = \int_0^\infty \frac{k_0^e(1-z)}{e^{\alpha z t}p(0)}dt$$
$$\Rightarrow \quad p(0) = \frac{k_0^e(1-z)}{\alpha z S_0} \qquad (36)$$

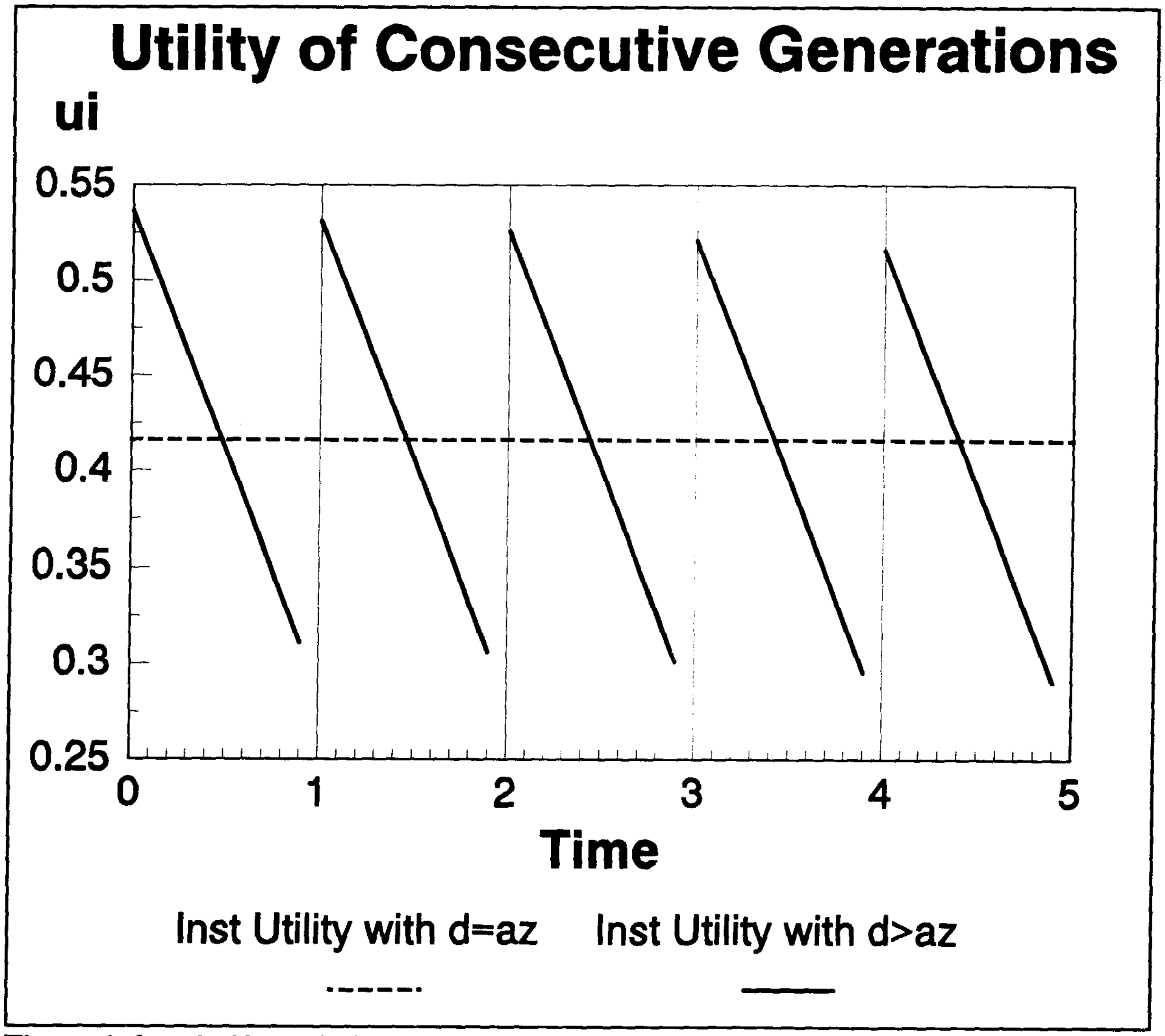

Figure 1.6 Welfare of Five Consecutive Generations

It remains to examine the significance of the assumption $\delta = \alpha z$. With $\delta \neq \alpha z$, every generation would shift parts of its capital endowment across time through saving or borrowing. Subsequently, net investment in the economy would not equal resource profits. The continuity of consumption across generations would break down and, hence, the behaviour of one infinitely living generation and many short living generations would no longer be identical. For a numerical example ($p(0) = 1$, $\alpha = 1$, $k^e_0 = 5$, $z = 0.5$), Figure 1.6 shows instantaneous utility of five consecutive generations. With $\delta = 0.5$ ($\delta = \alpha z$), instantaneous utility is constant within and across generations. With $\delta = 0.75$ ($\delta > \alpha z$), every generation moves consumption toward earlier times (borrowing from the own generation's endowment, $X(t) < 0$, is allowed in this model). Also, total utility drifts downward from generation to generation. Hartwick's rule is violated with $X(t) \neq 0$ and the constant utility path does not hold any more. With $\delta < \alpha z$, instantaneous utility would increase within the lifetime of any generation, and utility across generations would drift upward.

In this model of discrete generations, $\delta \neq \alpha z$ leads to non-zero investment due to the changes in the population's age distribution with time. In a more realistic model of a continuum of overlapping generations, the population's age distribution would be uniform and constant. Then, $X(t) \neq 0$ if $\delta \neq \alpha z$ still holds for each individual generation. However, since net savings aggregated over one generation's life are zero, net savings aggregated over a population with uniform age distribution would be zero at any one point in time as well. Hence, $X(t)$ would be constant across time, net investment would again equal resource profits, and the constant welfare path would be obtained without any restrictions on the utility discount rate δ. Hence, the assumption $\delta = \alpha z$ could be dropped in a more realistic model with uniform age distribution.

3.2.2 Compensation with Private Resource Ownership

In the previous section it was assumed that resources are publicly owned and sold to the current generation at an administered price. This section addresses the question, under which conditions a constant welfare path through Hartwick's rule can be obtained if resources are privately owned. It is assumed that all resources are owned by the first generation. The government could tax hundred percent of resource profits and invest the proceeds in perpetuity. Under this policy, private resource ownership would be essentially meaningless. Owners would not receive any benefits from selling their resources. Hence, they would have no incentive to optimize resource depletion across time, and, in order to achieve efficient depletion, resource prices would have to be administered as under public ownership.

Alternatively, the government could observe resource profits and raise revenues of the same amount through an endowment tax that is invested in perpetuity. Under this mechanism, resource owners retain the incentive for efficient depletion. Also, if parts of the capital stock are bequeathed to the next generation, as it can often be observed in the real world, governments can reduce their compensating investment accordingly. The first generation would sell a part of the resource stock to the second generation, the second generation would sell a part to the third and so on. However, the resource profits gained by the first generation from selling part of the stock to the second generation would be fully recovered as an endowment tax, invested by the government, and thus fully returned to the second generation as their endowment. The same procedure would take place between the second and third and all following generations. The net effect is that the resource stock is privately owned at all times, every generation invests the resource profits from own consumption in perpetuity, and the endowment effect of resource ownership by the first generation is eliminated through the endowment tax set equal to resource profits. If all generations followed this mechanism, and the resource price under this mechanism was efficient, it would meet all conditions of Hartwick's rule and, hence, a constant welfare path would be the result.

If it was common knowledge that every generation will follow Hartwick's rule, the resulting resource price must be efficient since arbitrage profits could be made otherwise. Common knowledge implies that every generation knows that every following generation will follow Hartwick's rule; it also implies that every generation knows that every following generation knows that every following generation will follow Hartwick's rule; and so on. If the assumption of common knowledge does not hold, however, the resulting price path may be inefficient. Consider the following example of the continuous time model used in section 3.2.1. Generation 0 follows Hartwick's rule. However, generation 0 believes that generation 1 will be selfish and not follow Hartwick's rule but instead consume all of the capital stock and all of the remaining resource (generation 2 would not be able to buy any of the resource from generation 1 since it does not inherit a capital stock which it could use to purchase the resource). This belief of generation 0 would change the anticipated demand for the resource from generation 1, and hence change the resource price in the present.

Figure 1.7 depicts such an example (for $S_0 = 5$, $k^e_0 = 1$, $\alpha = 0.5$, $z = 0.5$, and $\delta = 0.25$) and compares it to a situation of common knowledge about all generations following Hartwick's rule. If the first generation expected repudiation by the second, the resource price would be lower, and generation 1 and 2's welfare higher than under common knowledge. All generations after time 2 would suffer from welfare of minus infinity. Note that, if generation 0 expects generation 1 to repudiate, however, generation 1 does not repudiate but follows Hartwick's rule, the resource price would jump at time 1. Since generation 0 would have over-consumed, based on its faulty assumption that generation 1 will repudiate, it would be impossible for following generations to achieve the constant welfare level of the common knowledge scenario even if all generations actually followed Hartwick's rule.

The discussion has shown that a constant welfare path can, theoretically, be achieved under private resource ownership through government investments following Hartwick's rule alone. However, the requirement of common knowledge underlines the fragility of market prices as indicators of scarcity, and hence as indicators of the required compensatory investment, in an intergenerational context. It follows that for Hartwick's rule to work in a

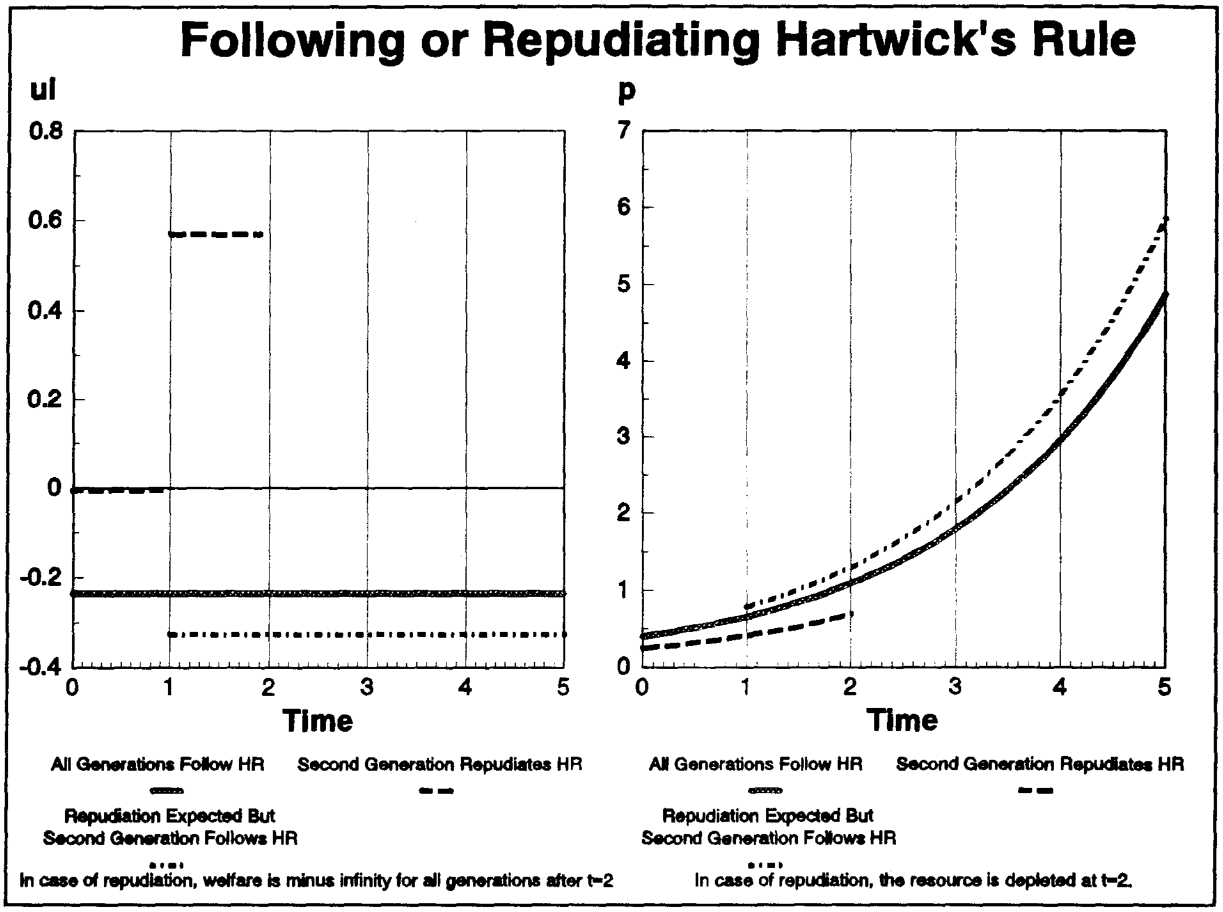

Figure 1.7 Following or Repudiating Hartwick's Rule

private ownership economy, it is necessary that all market participants base their expectations on common knowledge that Hartwick's rule will be followed. Hence, if a sustainability objective was implemented based on Hartwick's rule, it would be important for the government to not just quietly invest, but to explicitly state the sustainability policy and commit to following it in perpetuity. This suggests a rationale for introducing sustainability as an explicit policy objective, possibly including legal obligations that would have at least some commitment value for future generations.

4 Conclusions

The work of resource economists has long focussed on intertemporally efficiency resource use. This has resulted in policies emphasizing the establishment and securement of resource property rights within the current generation. Institutional arrangements for intra-generational resource ownership have evolved. Yet, there are no institutional arrangements for the distribution of resource endowments across generations. The intergenerational general equilibrium models in this chapter have demonstrated that if an early generation assumes ownership of the resource stock, subsequent generations would face steeply declining levels of welfare even if the resource is depleted efficiently. The models show how "... a [resource depletion] program can be intertemporally efficient and yet be perfectly ghastly." (Dasgupta and Heal 1979, p.257). Since these models abstract from uncertainty and technological progress, they are too simplistic to predict doom for future generations. Yet, they clearly show that efficient resource markets alone do not ensure a reasonable welfare level for future generations. Hence, striving for intertemporal efficiency in an intergenerational context would be incomplete without agreement on some basic principles of intergenerational resource distribution.

The concern about intergenerational welfare distribution arises because of systematic biases in favour of earlier generations. Earlier generations are in a position to make assumptions on resource ownership and impose them unilaterally and irreversibly on later generations. The models have shown that shifting resource endowments from future generations to the present unambiguously increases the welfare of the current generation. Hence, an early generation that maximizes its own welfare would have an incentive to assume ownership of the full resource stock generating a systematic bias against the welfare of future generations.

The concerns about intergenerational justice are aggravated by observations of current depletion practices. While, in the past, population and technology were at a level that prevented an early generation from depletion at a level that could cause global, long-term welfare effects, this has changed with the increase in human population and technological advances that allow resource depletion at a truly global scale. Casual evidence of the current practice of resource extraction confirms the view that the current generation assumes ownership of the full resource stock. Political decision making on resource depletion seem to include some consideration of depletion efficiency. However, little thought appears to be given to the issue of intergenerational welfare distribution. Subsequently, depletion rates and resource prices would be based on assumptions about resource distribution that are biased in favour of the current generation. Since, in general, resource prices depend on the assumption on which generations own the resource, there is no basis for the claim that interference with resource market prices would imply deviations from the "right price", unless the current assumptions about resource ownership are explicitly endorsed.

The models in this chapter are sufficiently general to allow a broad interpretation of natural resources. Natural resources would not only include the typical non-renewable resources, such as fossil fuels and minerals, but also other types of natural capital, such as depletion of the ecosphere's capacity to absorb human waste products. While the scarcity of source constraints (fuels or minerals) has often been overestimated in the past, the scarcity of sink constraints (absorption capacity for emissions etc.) has traditionally been underestimated. Applied to emissions, the models of this chapter would suggest that the implementation of a mechanisms that ensures efficiency (for example, a Pigou tax or an intergenerational market for pollution rights) is insufficient for an optimal policy. An optimal policy would have to includes consideration of the endowment effect from assigning pollution rights to different generations since all types of natural capital depletion can lead to negative endowment effects for the welfare of future generations unless those are explicitly compensated for the damage imposed on them (see also Bromley 1989 who discussed this income effect).

Howarth and Norgaard (1990) suggest that the optimal, as opposed to merely efficient, allocation of resources can be determined by maximizing a social welfare function by choice of intergenerational resource endowments. This chapter has shown, in a model with more than two generations, that the resulting resource endowments can easily be inefficient because of the lack of markets between non-adjacent generations. This would lead to a resource price rising at a rate below the discount rate. In these cases, future generations are given ownership over a share of the resources for distributional reasons. However, for efficiency reasons, earlier generations should be able to use the resource and hence, need to be able to buy the resource from later generations. Since a desired intergenerational welfare distribution may not be achievable through efficient redistribution of resource endowments, explicit compensation mechanisms that could efficiently achieve the desired intergenerational welfare distribution have been discussed in the second part of this chapter.

The models in section 3 have demonstrated how Hartwick's rule for compensating for resource depletion through capital investment can bring about constant welfare across generations. For Hartwick's rule to work in an economy with privately owned resources, it must be common knowledge that all generations will follow Hartwick's rule. This underlines the relevance of explicitly stating or legislating sustainability as a policy objective. Alternatively, a compensation mechanism under public resource ownership is explored. Under the suggested mechanism, the resource would not be owned by any single generation. Instead, every generation would have the right to acquire the resource if it leaves behind compensatory investment that allows the achieved utility level to be sustained by future generations. Under this mechanism, the efficient resource price would have to be administered.

Price administration would be feasible in a simple world of certainty. In the real world, however, resource price administration would open the door to a range of problems of misuse and potential inefficiencies involving the incentives of individual decision makers. Hence, institutional arrangements for the implementation of the optimal depletion path without administering the resource price would be desirable. In a separate paper (von Amsberg 1992) I explore a market mechanism that would lead to the desired resource depletion path under full private ownership of the resource stock by the current generation. However, those who own and deplete a resource would have to insure themselves against the claims of future generations on welfare equal to the welfare enjoyed by the depleting generation. A competitive insurance industry would offer such insurance to resource owners and would effectively act as the agent of future generations on today's resource markets. Future generations would hold claims against the insurance companies on payment of compensation for resource depletion. The insurance companies would, thus, undertake the task of investing the compensation for resource depletion. Such a regime would be particularly suitable for efficient handling of the uncertainty inherent in future generations' welfare in the real world. This approach would imply a drastic change in the concept of resource ownership from the right to use or dispose of a resource as one pleases to the right to use a resource such that the benefits of such use benefit all generations equally.

The most significant omission of this paper is uncertainty. In real life, there are different types of uncertainty that render the implementation of any mechanism for intergenerational justice highly complex. The stock size of natural resources is uncertain. In the last decades, predictions about the quantity of reserves of non-renewable resources were frequently updated, mostly upwards. On the other hand, only recently did we learn that the absorptive capacity of the biosphere for many waste products is already exhausted. Our incomplete knowledge of nature leads us to deplete natural capital in some instances without knowing about it (such as CFC or carbon dioxide emissions in the past). Technological change introduces another dimension of uncertainty. Technology can work in either direction: it can alleviate concerns about resource depletion if it leads to discovery of sustainable substitutes, but it can also aggravate concerns about resource depletion if it leads to new uses for natural resources. Other dimensions of uncertainty involve the size of future generation and even their preferences. How do we know that future generations will enjoy driving cars as much as the current generation does? All these uncertainties are likely causes of non-marginal changes in the economy that would change relative prices. However, if relative prices change, compensatory investment calculated at previous price levels can easily become inadequate. Some of the complications resulting from uncertainty will be addressed in the following three chapters.

Appendix I-A: Derivation of the Equilibrium for the N-Generation Model

The first generation i = 1 faces the maximization problem:

$$\max_{K^c_{1,1},R^c_{1,1},K^c_{1,2},R^c_{1,2}} \quad U_1 = z\,Log[K^c_{1,1}] + (1-z)\,Log[R^c_{1,1}] + \delta\left(z\,Log[K^c_{1,2}] + (1-z)\,Log[R^c_{1,2}]\right)$$

$$s.t.\quad \frac{\alpha\,(K^e_1 - K^c_{1,1}) - K^c_{1,2}}{p_2} + \beta\,(R^e_1 - R^c_{1,1}) - R^c_{1,2} = 0 \tag{37}$$

The first order conditions can be solved for the following demands:

$$K^c_{1,1} = \frac{(\alpha K^e_1 + \beta p_2 R^e_1)z}{\alpha(1+\delta)} \qquad R^c_{1,1} = \frac{(\alpha K^e_1 + \beta p_2 R^e_1)(1-z)}{\beta p_2(1+\delta)}$$

$$K^c_{1,2} = \frac{\delta(\alpha K^e_1 + \beta p_2 R^e_1)z}{1+\delta} \qquad R^c_{1,2} = \frac{\delta(\alpha K^e_1 + \beta p_2 R^e_1)(1-z)}{p_2(1+\delta)} \tag{38}$$

The last generation i = N faces the following maximization problem:

$$\max_{K^c_{N,N},R^c_{N,N},K^c_{N,N+1},R^c_{N,N+1}} \quad U_N = z\,Log[K^c_{N,N}] + (1-z)\,Log[R^c_{N,N}] + \delta\left(z\,Log[K^c_{N,N+1}] + (1-z)\,Log[R^c_{N,N+1}]\right)$$

$$s.t.\quad K^e_N - K^c_{N,N} - \frac{K^c_{N.N+1}}{\alpha} + p_N\left(R^e_N - R^c_{N,N} - \frac{R^c_{N,N+1}}{\beta}\right) = 0 \tag{39}$$

The first order conditions can be solved for the following demands:

$$K^c_{N,N} = \frac{(K^e_N + p_N R^e_N)z}{1+\delta} \qquad R^c_{N,N} = \frac{(K^e_N + p_N R^e_N)(1-z)}{p_N(1+\delta)}$$

$$K^c_{N,N+1} = \frac{\alpha\,\delta\,(K^e_N + p_N R^e_N)z}{1+\delta} \qquad R^c_{N,N+1} = \frac{\beta\,\delta\,(K^e_N + p_N R^e_N)(1-z)}{p_N(1+\delta)} \tag{40}$$

The utility maximization problem of all intermediate generations, i = 2,...,N-1, is more complicated since they can trade twice, at times t = i and t = i+1. Their problem is solved in two steps. At time i+1, they face the following maximization problem contingent on their investments in the previous period, K^i_i and R^i_i:

$$\max_{K^c_{i,i+1}, R^c_{i,i+1}} \quad u_{i,i+1} = z Log[K^c_{i,i+1}] + (1-z) Log[R^c_{i,i+1}] \qquad \textbf{(41)}$$
$$s.t. \quad \alpha K^i_i - K^c_{i,i+1} + p_{i+1}(\beta R^i_i - R^c_{i,i+1}) = 0$$

The solution to this problem is:

$$K^c_{i,i+1} = (\alpha K^i_i + \beta p_{i+1} R^i_i) z \qquad R^c_{i,i+1} = \frac{(\alpha K^i_i + \beta p_{i+1} R^i_i)(1-z)}{p_{i+1}} \qquad \textbf{(42)}$$

The choices at t = i+1 are substituted into the following maximization problem at t = i:

$$\max_{K^c_{i,i}, R^c_{i,i}, K^i_i, R^i_i} \quad U_i = z Log[K^c_{i,i}] + (1-z) Log[R^c_{i,i}] + + \delta \left(z Log[K^c_{i,i+1}] + (1-z) Log[R^c_{i,i+1}]\right) \qquad \textbf{(43)}$$
$$s.t. \quad K^e_i - K^i_i - K^c_{i,i} + p_i(R^e_i - R^i_i - R^c_{i,i}) = 0$$

The first order conditions produce the Hotelling price path: $p_{i+1} = (\alpha/\beta)\, p_i$. This condition has to hold for an interior solution. Now, there are three first order conditions left for each of the N-2 intermediate generations. In addition, there are N-1 market clearing conditions:

$$\beta R^i_{i-1} + R^e_i = R^c_{i-1,i} + R^c_{i,i} + R^i_i \quad \forall\, i = 2,...,N \qquad \textbf{(44)}$$

and R^i_1 is trivially R^c_1 - $R^c_{1,1}$. This are 3(N-2)+N-1 equations, which can be solved for 4(N-2) choice variables and one price. All other prices are then determined through the Hotelling rule. Demands and prices for all generations can be expressed with $p_1 = (\beta/\alpha)\, p_2$ as:

$$K_{i,i}^{c} = \frac{(K_i^e + p_i R_i^e)z}{1+\delta} \qquad R_{i,i}^{c} = \frac{(K_i^e + p_i R_i^e)(1-z)}{p_i(1+\delta)}$$
$$K_{i,i+1}^{c} = \frac{\alpha\,\delta\,(K_i^e + p_i R_i^e)z}{1+\delta} \qquad R_{i,i+1}^{c} = \frac{\beta\,\delta\,(K_i^e + p_i R_i^e)(1-z)}{p_i(1+\delta)} \tag{45}$$

$$p_i = \frac{\alpha^{i-1}(1-z)\sum_{j=1}^{N}\frac{K_j^e}{\alpha^{j-1}}}{\beta^{i-1}z\sum_{j=1}^{N}\frac{R_j^e}{r^{j-1}}} = \frac{\alpha^{i-1}(1-z)\sum_{j=1}^{N}\frac{K_j^e}{\alpha^{j-1}}}{\beta^{i-1}zS_0} \tag{46}$$

Intermediate generations' demands could be directly derived for every generation separately if the Hotelling price path is assumed. However, prices and investments can only be calculated by solving the first order conditions for all intermediate generations simultaneously with the market clearing conditions since individual generations are indifferent between investment in R and K if the Hotelling price path holds.

Appendix I-B: Derivation of the Three Generation Equilibrium with $K^i_2 = 0$

In a three generation equilibrium with $K^i_2 = 0$, demands of generation 1 and 3 are the same as in the interior solution (Appendix I-A). Since generation 2 invests resources only, the optimal choices at time t = 3 are:

$$K_{2,3}^{c} = \beta p_3 R_2^i z \qquad R_{2,3}^{c} = \beta R_2^i (1-z) \tag{47}$$

The optimization problem of generation 2 is:

$$\max_{K_{2,2}^c, R_{2,2}^c, R_2^i} \quad U_2 = z\,Log[K_{2,2}^c] + (1-z)\,Log[R_{2,2}^c] + \\ + \delta\left(z\,Log[K_{2,3}^c] + (1-z)\,Log[R_{2,3}^c]\right) \tag{48}$$
$$s.t. \quad K_2^e - K_{2,2}^c + p_2(R_2^e - R_2^i - R_{2,2}^c) = 0$$

The resulting demands with z = 0.5 and $\beta = 1$ are:

$$K^c_{2,2} = \frac{K^e_2 + p_2 R^e_2}{2(1+\delta)} \qquad R^c_{2,2} = \frac{K^e_2 + p_2 R^e_2}{p_2 2(1+\delta)}$$

$$K^c_{2,3} = \frac{\delta p_3 (K^e_2 + p_2 R^e_2)}{2(1+\delta)} \qquad R^c_{2,3} = \frac{\delta (K^e_2 + p_2 R^e_2)}{p_2 2(1+\delta)} \tag{49}$$

The prices are:

$$p_2 = \frac{(1+\delta)\alpha K^e_1 + (1+2\delta) K^e_2}{(1+\delta) R^e_1 + R^e_2}$$

$$p_3 = \frac{((1+\delta)\alpha K^e_1 + (1+2\delta) K^e_2) K^e_3}{\delta K^e_2 R^e_1 + \alpha \delta K^e_1 R^e_2 + 2\delta K^e_2 R^e_2 + (1+\delta)\alpha K^e_1 R^e_3 + (1+2\delta) K^e_2 R^e_3} \tag{50}$$

CHAPTER II

INEFFICIENCIES FROM INCOMPLETE INTERGENERATIONAL INSURANCE MARKETS

1 Introduction

The current generation, due to its population size and its technological capabilities, has an unprecedented ability to affect the welfare of future generations. Many effects on the welfare of future generations occur through externalities, such as the long-term impacts of pollution or changes to the production possibilities through technological progress. The market failures resulting from such technological externalities[1] are well recognized for intra-generational decision making and are directly applicable to intergenerational decision making, as well. This chapter does not analyze these intergenerational externalities. Instead it deals with situations in which an earlier generation affects future generations' welfare by making investments that reduce or increase the uncertainty faced by future generations through market mechanisms.

Examples of investments that change the uncertainty faced by future generations through market transactions include all types of insurance investment. Protective measures against natural or human-made disasters, such as building a dam against flooding, fall into this category. Similarly, the preservation of biodiversity can be viewed as an investment that reduces the uncertainties faced by future generations by providing options that pay off in bad

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[1] In common usage, the term externalities refers to technological externalities only. Technological externalities are those where non-price variables in the production or utility function of one agent are chosen by another agent. In contrast, pecuniary externalities result from price changes in the economy, and, in general, do not constitute a market failure (see Baumol and Oates 1988).

states of the world, such as climatic changes or degeneration of important seeds. Often, such insurance investments have to be made across generational time. They involve investment decisions of one generation that pay off only to future generations. There are other investments of the current generation that lead to specialization and increase the uncertainty faced by future generations. In both cases, the returns to investment are assumed to be sold to future generations through markets. They do not constitute a technological externality, in which case the market failure would be obvious.

This chapter is motivated by the question whether competitive markets lead to efficient levels of intergenerational investment under risk. The analysis leads to a market failure that is based on the incompleteness of inter-generational insurance markets. Consider the following stylized example to motivate the following analysis. The example consists of a simple endowment economy with only one consumption good and two overlapping generations. Both generations are risk averse. Generation 1 lives at time 1 and 2, receives an endowment of 10 units of the consumption good at time 1 and consumes only at time 2. Generation 2 lives and consumes at time 2 only. Generation 2 receives an endowment of 10 at time 2. At time 2, a flood may strike with a 50 percent chance. The flood would destroy all of generation 2's endowment.

At time 1, generation 1 could build a dam that would protect the endowment of generation 2 from the uncertain flood. At time 2, it would be too late to build the dam. Generation 1 does not receive any direct benefits from the dam. However, it can sell the dam to generation 2 at time 2, after information is received on whether the flood will strike but before the flood actually occurs. The cost of building the dam is 5 units of the consumption good. First, it will be shown that generation 1 would not build the dam under these circumstances. Then, it will be shown that the decision not to build the dam is inefficient. If generation 1 decided to build the dam, it would sell the dam to generation 2 since generation 1 itself does not receive direct benefits from the dam. Assuming a competitive market for the dam, generation 2 would buy the dam at a price equalling its marginal benefits. If the flood is known to occur, generation 2 would pay at most 10 for the dam. If the flood is known not to occur, there is no benefit from the dam and generation 2 would not be willing to pay anything for the dam. Generation 1 would have the alternative of not building the dam and consuming 10, or building the dam and consuming 15 if the flood occurs and 5 if it does not occur. Note that the expected value of generation 1's consumption is the same in both cases. Since generation 1 is risk averse, it prefers certain consumption of 10 to risky consumption with the same expected value and would not build the dam.

Now suppose generation 2 was able to commit itself to buying the dam at time 1 (before it is born and before the uncertainty is resolved). At time 1, generation 2 could buy the dam at its cost, 5, and leave generation 1 indifferent as to whether the dam was built or not. It would be up to generation 2 to decide whether the dam was built. If the dam was built, generation 2 would consume 5 with and without the flood. If the dam was not built, generation 2 would consume 0 if the flood occurs and 10 if the flood does not occur. Since generation 2 is risk averse, it would prefer certain consumption of 5 over risky consumption with the same expected value and decide that the dam should be built. Hence, in the competitive solution the dam would not be built, but in the coordinated solution the dam would be built. Generation 1 is indifferent between the competitive solution (no dam is built) and the coordinated solution (the dam is built and generation 2 commits to buying ex-ante). Generation 2 strictly prefers the coordinated solution to the competitive outcome. Hence, the outcome of the coordinated solution Pareto-dominates the competitive solution. Therefore, the dam should be built, and the competitive solution is inefficient (see Table 2.1 for a summary of the pay-offs).

(G1/flood, G1/no flood) - (G2/flood, G2/no flood)	Competitive Solution (Generation 1 decides)	Coordinated Solution (Generation 2 decides)
Generation 1 does not build the dam.	(10,10) - (0,10)	(10,10) - (0,10)
Generation 1 builds the dam.	(15,5) - (0,10)	(10,10) - (5,5)

Table 2.1 Consumption in the Competitive and the Coordinated Solution

The reason for the inefficiency of the competitive solution is the incompleteness of intergenerational insurance markets. Since generation 2 is born into resolved uncertainty, there is no market on which it could buy the dam ex-ante. However, generation 2 would like to shift part of its wealth from the good state (no flood) to the bad state (flood). One way to do this is paying for the dam in the good state as well. Therefore, generation 2 would benefit from being able to commit itself to buying the dam ex-ante. However, there is no ex-post incentive to honour this hypothetical commitment if generation 2 is born into the good state (no flood). Since there are no markets for moving the wealth of generation 2 across states, building the dam requires generation 1 to take on the risk of the dam being worthless even though there would be no aggregate uncertainty if the dam was built. Subsequently, a risk averse generation 1 has an inefficiently low incentive to build the dam in the competitive solution.

The general observation that the incompleteness of markets between non-adjacent generations can lead to inefficiencies has first been made by Samuelson (1958) in a model under certainty. Without specific reference to the intergenerational framework, it is recognized that, with uncertainty, the incompleteness of insurance markets is a market failure that can lead to inefficiencies (Hart 1975, and Grossman 1977). Wright (1987) suggests the problem that future generations may wish to insure themselves against appearing in a bad state. More specifically, Howarth (1991) makes the observation that the incompleteness of insurance markets can lead to inefficiency in an overlapping-generations model with technological uncertainty. Neither of these papers analyzes the consequences of the market incompleteness. The results of this chapter are related to previous research that demonstrates how the arrival of information may reduce welfare by eliminating the possibility of mutually beneficial exchanges (see for example Akerlof 1970). Similar to models with information asymmetries, an uninformed agent (generation 1 is uninformed at the time it makes its investment decision) trades with an informed agent (generation 2). As a result, beneficial exchanges are foregone that would have been possible if both agents were uninformed at the time of trade.

This chapter formally analyzes the market failure that arises due to incomplete intergenerational insurance markets. This chapter shows the conditions under which the market failure will occur and describes the direction of its effects. The first section analyzes the nature of the inefficiency arising from incomplete inter-generational insurance markets in detail and derives specific results regarding over- or under-investment by the current generation. Examples for over- and under-investment are provided. The second section contains applications of the main result to insurance investments, such as protective measures against global warming, the conservation of biodiversity, and, finally, the depletion of a non-renewable resource.

A uniform approach for analyzing the market inefficiency is taken throughout this chapter. First, the competitive solution is determined by solving the maximization problem of two overlapping generations for the equilibrium with incomplete markets. Second, a coordinated solution is determined by making the hypothetical assumption that markets are complete and solving both generations' maximization problem. From work by Debreu (1959), Arrow (1964), and Radner (1972), we known that the market equilibrium based on complete markets is efficient. Hence, the coordinated solution is efficient. The effect of the market incompleteness is then determined by comparing the choice variables (i.e., the amount of insurance investment) in the competitive and the coordinated solution.

Throughout this chapter, it is assumed that the welfare of a generation can be sensibly defined across different states into which this generation could be born. There is some philosophical controversy about the identity of future generations (for a brief discussion see Howarth 1991). However, this assumption is not critical for the main intuition underlying the analysis of this chapter. If it is asserted that future generations cannot be sensibly defined across states into which they are born, the potential future generations born into different states of the world would have to be treated as distinct identities. This is the approach suggested by Wright (1987). Then, the welfare distribution across future generations born into different states becomes a distributional problem that would have to be approached by means of a social welfare function. With a social welfare function that has the form of an expected utility function, the results of this chapter would still be fully applicable. The maximization of a generation's utility function across different states would then be interpreted as the maximization problem of a social planner.

2 An Intergenerational Investment Model under Risk

There are two generations j (j = 1, 2). Generation 1 lives at times 1 and 2; generation 2 at time 2 only. There are two states of the world k (k = A, B). At time 1, there is uncertainty which of the two states, A or B, will occur at time 2. There is only one good that both generations consume at time 2 only. Both generations have von Neumann-Morgenstern utility functions, $U_j = \pi\, u_j[c_{jA}] + (1-\pi)\, u_j[c_{jB}]$ where c_{jk} denotes consumption of generation j in state k. π is the probability that state A occurs. Both generations are strictly risk averse ($u_j' > 0$, $u_j'' < 0$). At time 1, generation 1 receives an endowment, e_1, and can invest this endowment in state contingent production of the consumption good. The investment in state A is denoted i_A; subsequently $i_B = e_1 - i_A$. The output of production is $f_A[i_A]$ if state A occurs and $f_B[e_1-i_A]$ if state B occurs ($f_k' > 0$, $f_k'' \leq 0$). Generation 2 is born into one of the two states and receives the endowment e_{2A} or e_{2B} depending on which state occurs.

In this model, there are no trade opportunities since there is only one good in each state. Trade across states is impossible since generation 2 is born into one of the two states and, therefore, cannot trade with generation 1 at time 1. Generation 1 solves the following maximization problem:

$$\max_{i_A} \quad U_1 = \pi u_1[f_A[i_A]] + (1-\pi) u_1[f_B[e_1-i_A]] \tag{1}$$

Let i_A* denote the investment in state A chosen in the competitive solution. Then, i_A* is determined by the following first-order condition:

$$\pi u'_{1A} f'_A = (1-\pi) u'_{1B} f'_B \tag{2}$$

where u'_{1A} and u'_{1B} denote marginal utilities with $i_A = i_A{}^*$. This first-order condition determines $i_A{}^*$ uniquely since the LHS of (2) is strictly decreasing in $i_A{}^*$ while the RHS is strictly increasing. Generation 2 has no choices to make and consumes its endowments in the respective state ($U_2 = \pi\, u_2[e_{2A}] + (1-\pi)\, u_2[e_{2B}]$).

To calculate the efficient coordinated solution, it is assumed that markets are complete and generations can trade the consumption good across states. Let t denote the quantity of consumption in state B that generation 1 buys from generation 2 against payment of the quantity p·t of the consumption good in state A. Hence, p is the price of consumption in state B in terms of consumption in state A. Utilities are the same as before, however, they are now denoted with V to distinguish equilibrium utility values from the competitive solution. Now the maximization problem of generation 1 is:

$$\max_{i_A, t} \; V_1 = \pi v_1[f_A[i_A] - pt] + (1-\pi) v_1[f_B[e_1 - i_A] + t] \tag{3}$$

with the first order conditions:

$$\pi v'_{1A} f'_A = (1-\pi) v'_{1B} f'_B$$
$$\frac{(1-\pi) v'_{1B}}{\pi v'_{1A}} = p \tag{4}$$

where v'_{1A} and v'_{1B} denote marginal utilities with $i_A = i_A{}^{**}$, and $i_A{}^{**}$ denotes the investment in state A chosen in the coordinated solution. The second generation maximizes:

$$\max_{t} \; V_2 = \pi v_2[e_{2A} + pt] + (1-\pi) v_2[e_{2B} - t] \tag{5}$$

with the first order condition:

$$\frac{(1-\pi)v/_{2B}}{\pi\, v/_{2A}} = p \tag{6}$$

Combining (4) and (6):

$$\frac{v/_{1B}}{v/_{1A}} = \frac{v/_{2B}}{v/_{2A}} \tag{7}$$

gives the intuitive result that the ratio of marginal utilities between states must be equalized across generations in the coordinated solution. Given the assumptions on v and f, the first order conditions determine the unique solution.

Proposition 2.1: **Assume that the competitive solution is an interior solution (generation 1 invests a strictly positive amount in both states), and that in the competitive solution, generation 2 is relatively worse off in state A than generation 1, then the competitive solution implies that generation 1 under-invests in state A, compared to the efficient coordinated solution.**

Proof:

With i_A* as the investment level for the competitive solution for which (2) holds, and i_A** as the efficient investment level for the coordinated solution for which (4) holds, proposition 2.1 can be written as:

$$\begin{aligned} \frac{u/_{1A}}{u/_{1B}} > \frac{u/_{2A}}{u/_{2B}} \quad &\Rightarrow \quad i_A^{**} < i_A^{*} \\ \frac{u/_{1A}}{u/_{1B}} < \frac{u/_{2A}}{u/_{2B}} \quad &\Rightarrow \quad i_A^{**} > i_A^{*} \\ \frac{u/_{1A}}{u/_{1B}} = \frac{u/_{2A}}{u/_{2B}} \quad &\Rightarrow \quad i_A^{**} = i_A^{*} \end{aligned} \tag{8}$$

Now, the first part of (8) will be shown by contradiction. Hence, it is assumed that:

$$\frac{u'_{1A}}{u'_{1B}} > \frac{u'_{2A}}{u'_{2B}} \tag{9}$$

Combining (2) and (4) results in:

$$\frac{v'_{1A}}{v'_{1B}} \frac{f'_A[i_A^{**}]}{f'_B[1-i_A^{**}]} = \frac{u'_{1A}}{u'_{1B}} \frac{f'_A[i_A^{*}]}{f'_B[1-i_A^{*}]} \tag{10}$$

Suppose $i_A^{**} = i_A^{*}$. Then, (10) collapses to $v'_{1A}/v'_{1B} = u'_{1A}/u'_{1B}$. From this and $i_A^{**} = i_A^{*}$ follows $t = 0$ by comparing the definitions of U_1 and V_1. From U_2, V_2, and $t = 0$ follows $v'_{2A}/v'_{2B} = u'_{2A}/u'_{2B}$. From this and (7) follows $u'_{2A}/u'_{2B} = u'_{1A}/u'_{1B}$ which contradicts (9). Now suppose $i_A^{**} > i_A^{*}$. Then, (10) implies $v'_{1A}/v'_{1B} > u'_{1A}/u'_{1B}$. From this and $i_A^{**} > i_A^{*}$ follows $t > 0$ by comparing U_1 and V_1. From U_2, V_2, and $t > 0$ follows $v'_{2A}/v'_{2B} < u'_{2A}/u'_{2B}$. From this and (7) follows $u'_{2A}/u'_{2B} > u'_{1A}/u'_{1B}$ which contradicts (9). Since $i_A^{**} = i_A^{*}$ or $i_A^{**} > i_A^{*}$ are inconsistent with (9), from (9) must follow $i_A^{**} < i_A^{*}$. The proof for the second part of (8) is identical with all signs reversed.

The third part of (8) is also shown by contradiction. Suppose $u'_{2A}/u'_{2B} = u'_{1A}/u'_{1B}$ and $i_A^{**} > i_A^{*}$. With (10) this implies $v'_{1A}/v'_{1B} > u'_{1A}/u'_{1B}$. From this and $i_A^{**} > i_A^{*}$ follows $t > 0$ by comparing U_1 and V_1. From U_2, V_2, and $t > 0$ follows $v'_{2A}/v'_{2B} < u'_{2A}/u'_{2B}$. From this and (7) follows $u'_{2A}/u'_{2B} > u'_{1A}/u'_{1B}$ which contradicts $u'_{2A}/u'_{2B} = u'_{1A}/u'_{1B}$. With $i_A^{**} < i_A^{*}$, the same contradiction can be shown by reversing all signs. Since $i_A^{**} > i_A^{*}$ or $i_A^{**} < i_A^{*}$ are inconsistent with $u'_{2A}/u'_{2B} = u'_{1A}/u'_{1B}$, from $u'_{2A}/u'_{2B} = u'_{1A}/u'_{1B}$ must follow $i_A^{**} = i_A^{*}$. The coordinated solution was constructed as an Arrow-Debreu equilibrium with complete markets. Therefore, i_A^{**} is the efficient level of investment (Arrow 1964, and Debreu 1959).■

This general result can lead to inefficiently low or inefficiently high investment for the bad state in the competitive solution depending on the nature of the uncertainty. If generation 1 faces higher risk than generation 2, there will be excessive investment for the bad state; if generation 2 faces higher risk than generation 1, there will be insufficient investment for the bad state. A higher risk for generation 2 means that, in terms of ratios of marginal utilities, the bad state for generation 1 is worse for generation 2. This situation is depicted graphically in Figure 2.1. The following two examples analyze two types of uncertainty. First, endowment uncertainty (exogenous uncertainty) for generation 2 is assumed. This leads to under-insurance by generation 1.

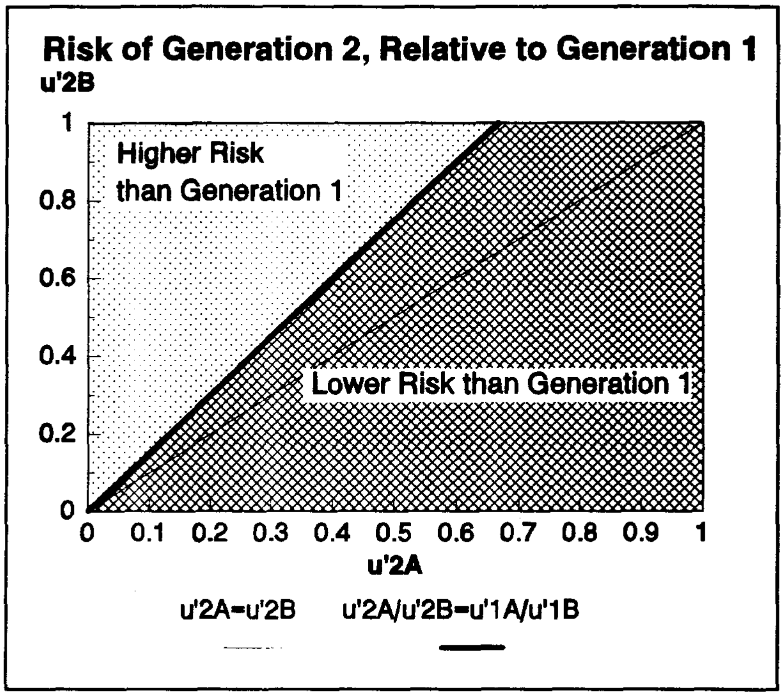

Figure 2.1 Relative Risk of Generation 2

Second, uncertainty about the return to investments rather than endowments is assumed. In the latter case, uncertainty is the outcome of the optimal investment decision by generation 1 (endogenous uncertainty) and leads to over-diversification of generation 1's investment in the competitive solution.

2.1 An Under-Insurance Example

The result that markets lead to under-insurance of risks that are higher for future generations than for the current generation is illustrated by means of the following simple example. The first generation receives an endowment, e_1, before the uncertainty is resolved and splits this endowment between investments in the consumption good in state A, i_A, and investment in the consumption good in state B, $i_B = e_1 - i_A$. Technology is linear, $f_k[i_k] = i_k$, and identical for the two states A and B, which are equally probable ($\pi = 0.5$). Generation 2 is born into either state A or B, facing endowment uncertainty ($e_{2A}/\pi < e_{2B}/(1-\pi)$). Hence, state A is the bad state. Both generations have log-utility. In the competitive solution, no trade can take place. Generation 2 consumes its endowment in the respective state. Generation 1 faces the following problem:

$$\max_{i_A} \; U_1 = \pi \, Log[i_A] + (1-\pi) Log[e_1 - i_A] \qquad \rightarrow \; i_A^* = \pi e_1 \tag{11}$$

However, through a coordination mechanism, generation 1 could insure generation 2 against the endowment uncertainty within the limits of generation 1's own endowment. In the coordinated solution, trade would be allowed and generation 1 would solve the problem:

$$\max_{i_A, t} \; V_1 = \pi \, Log[i_A - pt] + (1-\pi) Log[e_1 - i_A + t] \tag{12}$$

Generation 2 would solve the problem:

$$\max_{t} \; V_2 = \pi \, Log[e_{2A} + pt] + (1-\pi) Log[e_{2B} - t] \tag{13}$$

The resulting equilibrium would be:

$$\begin{aligned} p &= 1 \\ t &= e_{2A}\pi + e_{2B}\pi - e_{2A} \\ i_A^{**} &= \pi e_1 + \pi e_{2B} + (\pi - 1) e_{2A} \end{aligned} \tag{14}$$

Insurance investment (investment for the bad state) in the coordinated solution, i_A^{**}, exceeds that in the competitive solution, i_A^*, if $e_{2A} < \pi/(1-\pi)e_{2B}$, which is the case whenever A is, in fact, the bad state for generation 2. The numerical example in Figure 2.2 shows how the coordinated solution can lead to a Pareto improvement over the competitive solution. As a result of the linear technology, all gains from trade accrue to generation 2. Of course, the under-insurance result is the outcome of the assumed endowment structure. Over-insurance would occur if the first, and not the second generation received an uncertain endowment at time t=2. In that case, generation 2 could share some of generation 1's risk in a coordinated solution, resulting in less insurance investment compared to the competitive solution.

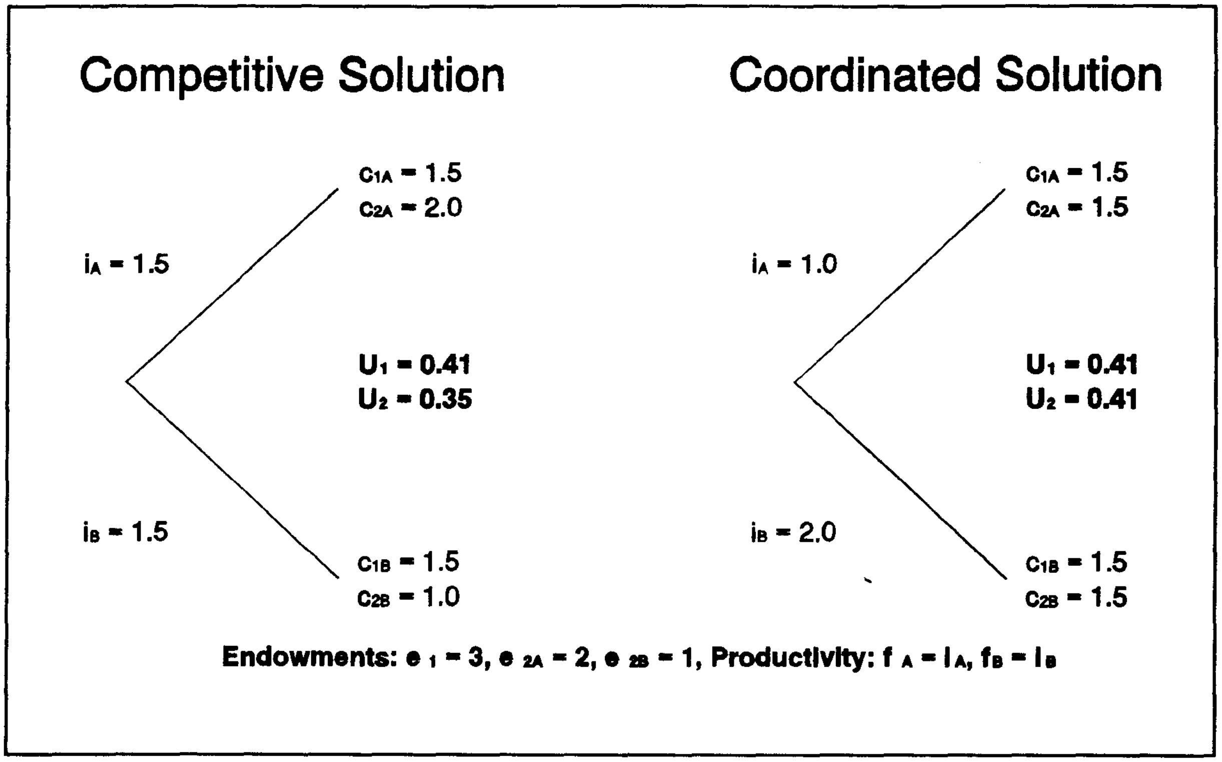

Figure 2.2 Under-Insurance with Exogenous Risk

2.2 An Over-Diversification Example

A different outcome results from endogenous uncertainty, as illustrated by the following example. Again, log-utility is assumed for both generations. While technology is still linear, investment in state A now yields a higher rate of return than investments in state B ($f_A[i_A] = a \cdot i_A$, $f_B[i_B] = b \cdot i_B$, $a \cdot \pi > b \cdot (1-\pi)$). In this example, there is no endowment uncertainty ($e_2 = e_{2A} = e_{2B}$). In the competitive solution generation 1 would again invest one-half of its endowment in each of the two states:

$$\max_{i_A} \; U_1 = \pi Log[a i_A] + (1-\pi) Log[b(e_1 - i_A)] \qquad \textbf{(15)}$$

$$\rightarrow \; i_A^* = \pi e_1$$

In the competitive solution, consumption of generation 2 would be e_2 in either state. In a coordinated solution, the risk of high return investment could be shared between both

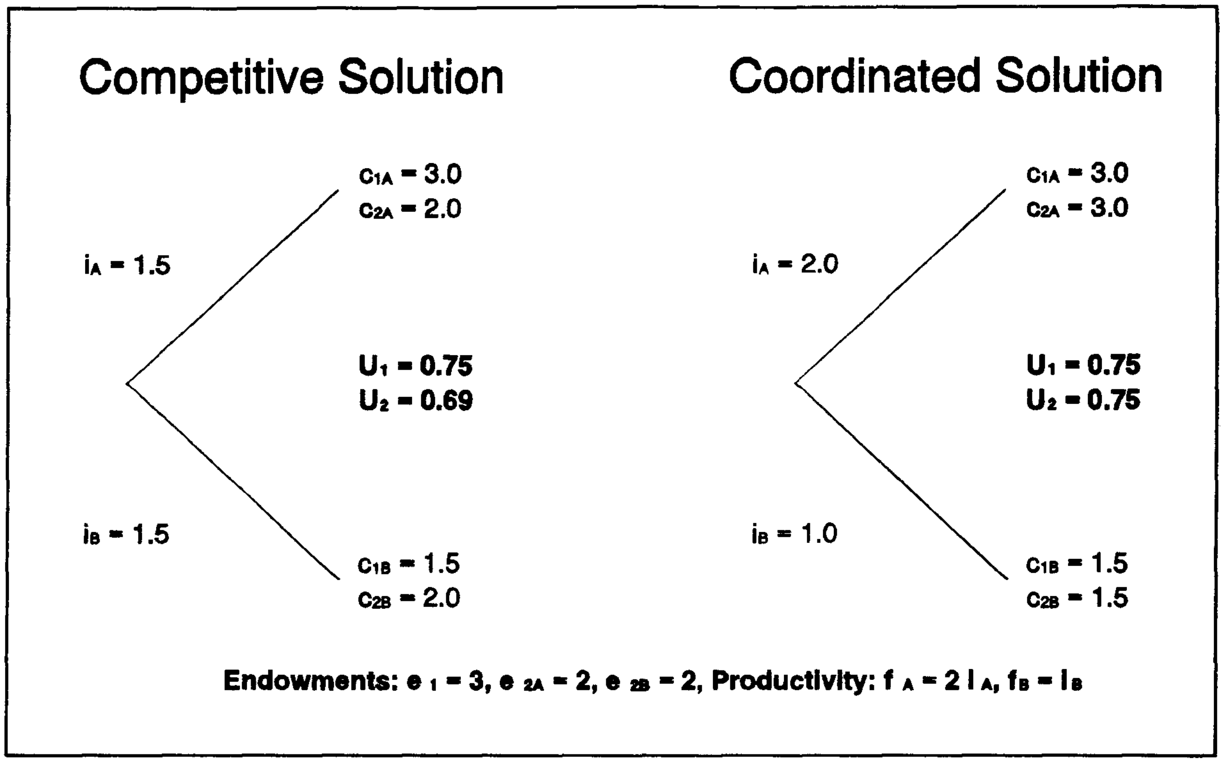

Figure 2.3 Over-Diversification with Endogenous Risk

generations which would induce generation 1 to increase investment in the high-return state A. The maximization problems for the coordinated solution are:

$$\max_{i_A,t} \; V_1 = \pi Log[a i_A - pt] + (1-\pi) Log[b(e_1 - i_A) + t] \tag{16}$$

and:

$$\max_{t} \; V_2 = \pi Log[e_2 + pt] + (1-\pi) Log[e_2 - t] \tag{17}$$

The resulting equilibrium is:

$$p = \frac{a}{b}$$

$$t = \frac{e_2(\pi a + \pi b - b)}{a} \qquad \textbf{(18)}$$

$$i_A^{**} = \pi e_1 + \left(\frac{\pi}{b} - \frac{1-\pi}{a}\right) e_2$$

In this example, i_A** (high return investment in the coordinated solution) is higher than i_A* (high return investment in the competitive solution) if a > $b(1-\pi)/\pi$ which is simply that investment in state A yields higher returns. Hence, the competitive solution implies inefficiently low risk taking by generation 1 or excessive diversification of investment. A numerical example is provided in Figure 2.3 and shows that the coordinated solution can results in a Pareto improvement over the competitive solution.

2.3 The Robustness of the Market Failure from Market Incompleteness

So far, the market failure resulting from incomplete intergenerational insurance markets has been shown in an extremely simplistic model with a single consumption good only. To understand the real life relevance of this market failure, it would be desirable to analyze the implications of relaxing some of the strict assumptions made before. The first extension of the model presented in the preceding section would allow generation 1 to consume at time 1 as well. With log-utility, generation 1 would spend a fixed proportion of its endowment value on consumption at time 1. Since prices are fixed through constant rates of return, they would not change with allowing consumption at time 1. Hence, consumption at time 1 would be unaffected by opening markets for consumption at time 2, and all previous results would remain unaffected. Similarly, letting generation 2 live for a second period and allowing it to consume at time 3 would not alter any results.

The introduction of additional goods may lead to the transmission of risks across generations through the prices for these other goods within each state. In order to test this intuition and the robustness of the main result in a more general setting, this section introduces a second consumption good. In the following models with more than one commodity, the efficient coordinated solution is derived as a Radner equilibrium, in which - in addition to spot markets within each state - contingent markets for one commodity in each state are opened before the uncertainty is resolved (Radner 1972). Under perfect foresight, such an equilibrium is efficient under conditions that are prevailing in the simple examples used here. Consider a model like the one used in the under-insurance example of the previous section. Generation 2 faces endowment uncertainty for good I. Now, there is a second good II, of which both generations receive a certain endowment. Within each state, both generations are free to trade goods I and II. For the competitive solution, both generations maximize their utility:

$$\max_{i_A, t_A, t_B} U_1 = \pi\left(Log[i_A - t_A p_A] + g\, Log[e_{1II} + t_A]\right) + (1-\pi)\left(Log[e_{1I} - i_A - t_B p_B] + g\, Log[e_{1II} + t_B]\right) \tag{19}$$

and:

$$\max_{t_A, t_B} U_2 = \pi\left(Log[e_{2IA} + t_A p_A] + g\, Log[e_{2II} - t_A]\right) + (1-\pi)\left(Log[e_{2IB} + t_B p_B] + g\, Log[e_{2II} - t_B]\right) \tag{20}$$

where subscripts 1 and 2 designate generation 1 and 2, respectively, subscripts I and II designate good I and II, respectively, and subscripts A and B designate state A and B, respectively. p_k is the price of good II in terms of good I in state k. The relative importance of good II is expressed by the parameter g. For the coordinated solution, trade across states is introduced (not shown here). The equilibrium investments in the competitive case, i_A*, and in the coordinated case, i_A**, are:

$$i_A^* = \frac{\pi\left((1+g)e_{1I}e_{1II} + g\,e_{1II}(e_{2IA}+e_{2IB}) + e_{1I}e_{2II}\right) - (g\,e_{2IA}e_{1II})}{(1+g)e_{1II} + e_{2II}} \tag{21}$$

$$i_A^{**} = \pi\,(e_{1I} + e_{2IA} + e_{2IB}) - e_{2IA}$$

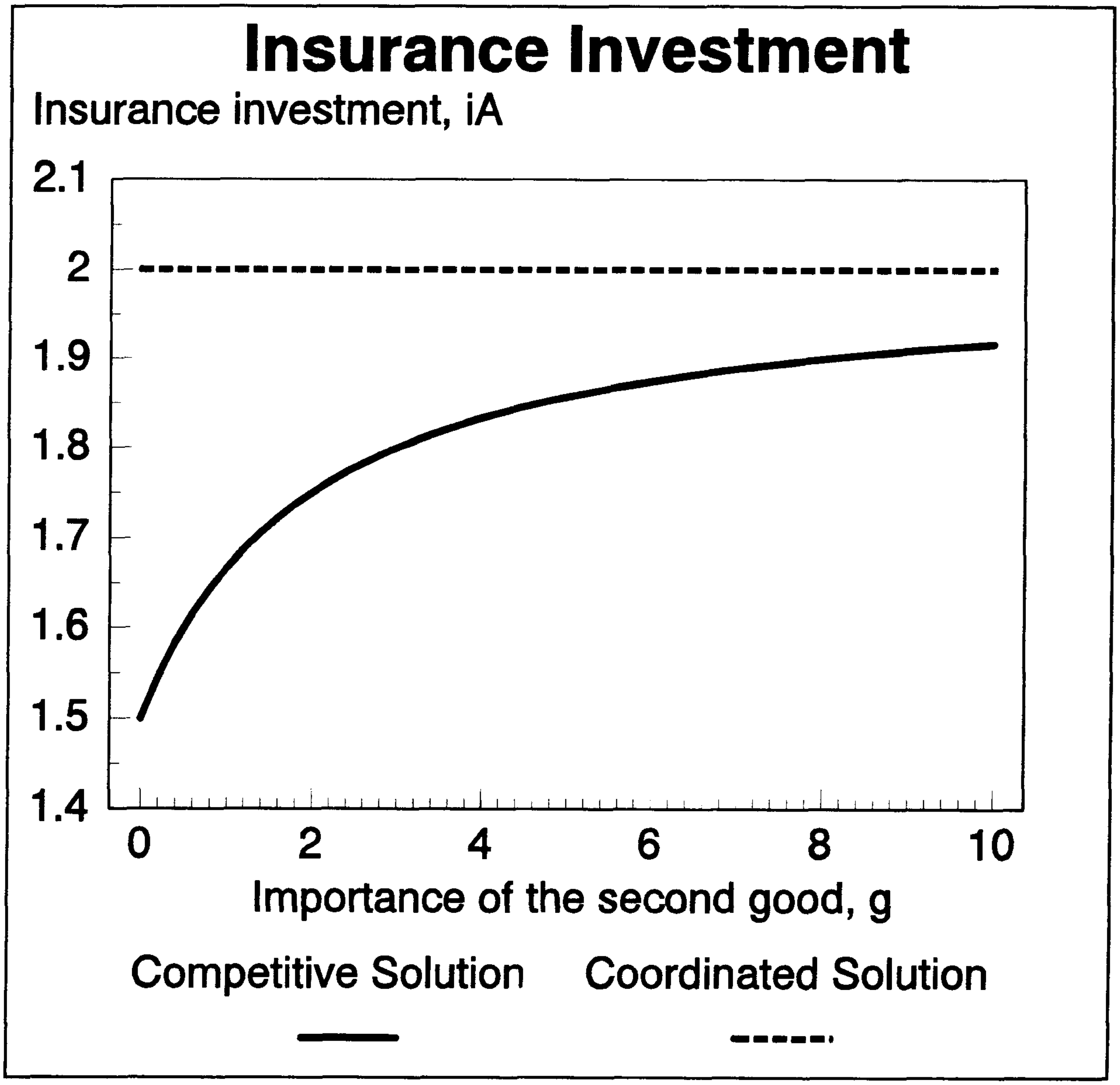

Figure 2.4 Insurance Investment and a Second Good's Importance

From equation (21) follows, with all endowments non-negative, that $i_A^{**} > i_A^*$ if $e_{2IA} < e_{2IB}\ \pi/(1-\pi)$which is that A is, in fact, the bad state. Hence, the under-insurance result holds for the case of a second good that enters the utility function concavely, though the extent of the inefficiency may be reduced. In particular, the extent of under-insurance is reduced with increasing the relative importance of good II, expressed by the parameter g. This effect is depicted in Figure 2.4 for a numerical example ($e_{1I} = 3$, $e_{1II} = 2$, $e_{2IA} = 1$, $e_{2IB} = 2$, $e_{2II} = 2$, $\pi = 0.5$). g = 0 would refer to the one good case shown in Figure 2.2. The rationale for the decrease of the inefficiency with introduction of a second good is that generation 2 faces endowment uncertainty for good I, and would like to shift some of this uncertainty to good II through trade within each state. Hence, in the good state, generation 2 sells relatively more (or purchases relatively less) of good I to (from) generation 1 as compared to the bad state. As a result, good II is cheaper in the bad state. Generation 1 faces some of generation 2's endowment uncertainty through the price mechanism within each state, and has an increased incentive to invest for the bad state. Hence, the relative risk of both generations is closer in the two-good model than in the one-good model. If generation 2, however, faced endowment uncertainty for good II as well, it would have less incentive to shift uncertainty to good II, and the introduction of a second good would not reduce the extent of the inefficiency in the competitive solution.

As an extreme case, consider a utility function in which the second good enters linearly. Now the maximization problems for the competitive solution are:

$$\max_{i_A t_A t_B} U_1 = \pi\left(Log[i_A - t_A p_A] + g_1(e_{1II} + t_A)\right) + (1-\pi)\left(Log[e_{1I} - i_A - t_B p_B] + g_1(e_{1II} + t_B)\right) \tag{22}$$

and:

$$\max_{t_A t_B} U_2 = \pi\left(Log[e_{2IA} + t_A p_A] + g_2(e_{2II} - t_A)\right) + (1-\pi)\left(Log[e_{2IB} + t_B p_B] + g_2(e_{2II} - t_B)\right) \tag{23}$$

The first order conditions are:

$$\begin{aligned} u'_{1IA}p_A &= u'_{1IIA} = g_1 \\ u'_{1IB}p_B &= u'_{1IIB} = g_1 \\ u'_{2IA}p_A &= u'_{2IIA} = g_2 \\ u'_{2IB}p_B &= u'_{2IIB} = g_2 \end{aligned} \tag{24}$$

and can be rearranged to:

$$\frac{u'_{1IA}}{u'_{1IB}} = \frac{u'_{2IA}}{u'_{2IB}} \tag{25}$$

With a quasi-linear utility function, generation 2 would try to shift all uncertainty to good II. As a result, trade between goods I and II within each state would be sufficient to equalize risk across generations in the competitive solution. Hence, with a quasi-linear utility function, the competitive solution is efficient. While proposition 2.1 is not violated, it has no relevance in this case since the condition that gives rise to the inefficiency cannot arise with this specific utility function. A quasi-linear utility function may have no empirical relevance, however, it is useful to point out this extreme condition under which the market failure would be remedied. The conclusion from this discussion is that the under-insurance effect will be large if generations are relatively risk averse, if there are relatively few goods over which risks can be spread, or if the risks are relatively large. This would focus real life concerns about this market failure on risks that have a large aggregate effect, such as possibly global warming.

3 Applications of the Under-Insurance Result

In this section, the principal ideas analyzed in an abstract manner in the previous section, are put to work in models closer to real-life environmental problems. First, a model of intergenerational insurance investment with a general production function and more than two states of the world is analyzed. Second, the example of insurance investment in building a dam that was presented in the introduction to this chapter is discussed in more detail.

Third, the conservation of biodiversity is analyzed as a problem that combines both generic situations that can lead to inefficiency: investment in insurance and specialization in investments that are more productive. Forth, the model is applied to the intergenerational depletion of a non-renewable resource. The purpose of that discussion is to analyze whether the incompleteness of markets impacts on the resource depletion path.

3.1 A Model of Insurance Investment

The following model of intergenerational insurance investment extends the original model to cases with more than two states and a generic type of insurance that is more realistic than the original model in which the first generation could only make investments that would directly offset the second generation's endowment uncertainty. As before, consider two overlapping generations 1 and 2. Both generations consume a single consumption good at time 2. However, generation 1 also lives at time 1 and receives its endowment, e_1, at time 1. Generation 2 is threatened with uncertain damage that reduces its endowment, e_2, by damage, d_k, depending on the state k into which generation 2 is born. Generation 1 can invest in insurance, i, at the cost c[i] ($dc/di > 0$, $d^2c/di^2 > 0$). Also $e_1 \geq i \geq 0$ must be fulfilled. Generation 1 has no direct benefit from the insurance, however, it can sell insurance at price p_k to generation 2 at time 2 in state k. Insurance decreases the damage d_k. Damage is always positive ($d_k > 0$). For all k, $d_k[i]$ is positive and decreasing in i ($dd_k/di < 0$, also assume $d^2d_k/di^2 > 0$). Assume that any states A and B can be ordered such that $A < B \Leftrightarrow d_A > d_B$ (state A is "worse " than state B), then it is assumed to be the nature of insurance, i, that $A < B \Leftrightarrow dd_A/di < dd_B/di$ for all i. This means, in a good state of the world damage is small and benefits from insurance are small as well. The net marginal costs of insurance (marginal cost minus marginal benefit) are lower in bad states than in good states. An example of damage and net marginal costs in different states as a function of insurance, i, is shown in Figure 2.5.

Both generations have von-Neumann-Morgenstern utility functions and are strictly risk-averse. Utility for both generations is defined across states ($U_j = \Sigma_k \pi_k u_j(c_{jk})$, $j = 1, 2$;

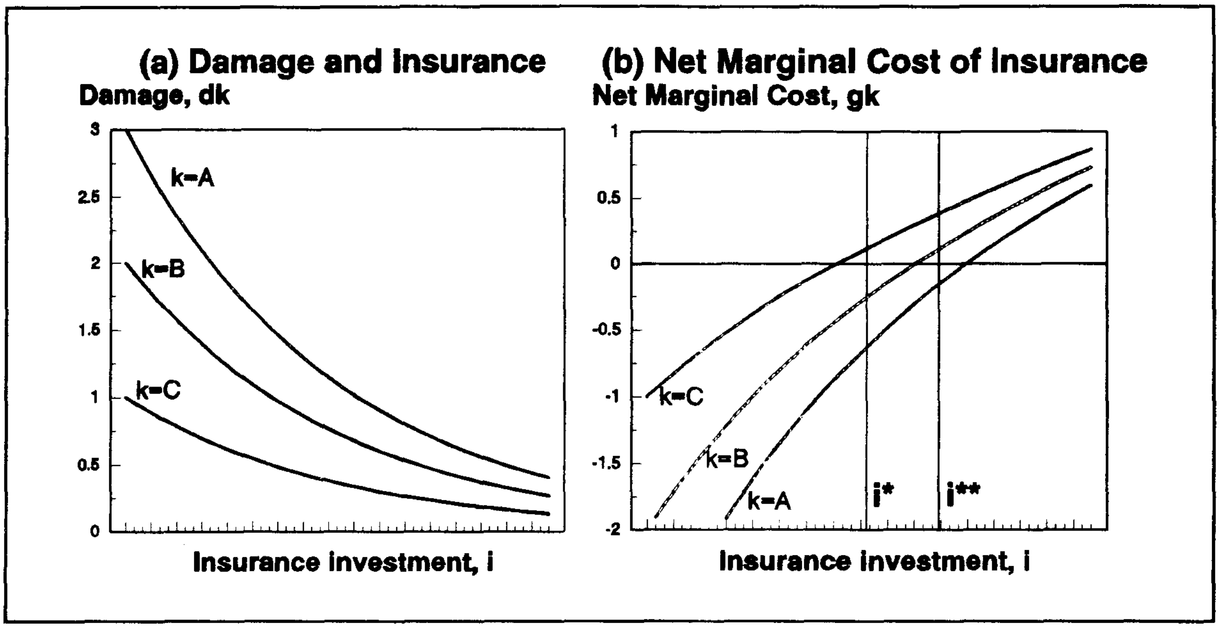

Figure 2.5 Damage and Net Marginal Cost of Insurance Investment

$u'_j > 0$, $u''_j < 0$). Generations have perfect foresight and behave competitively. First, the competitive solution will be determined. Second a coordinated solution for hypothetically complete ex-ante markets will be determined and compared to the former.

3.1.1 The Competitive Solution

Trade between generations is possible only at time 2 after uncertainty is resolved. Hence p_k is the ex post price at which generation 1 sells insurance to generation 2 in state k. Generation 2 maximizes utility within each state:

$$\max_{i_k} \quad u_2\left[e_2 - d_k[i_k] - p_k i_k\right] \tag{26}$$

resulting in the first order conditions:

$$p_k = -\frac{dd_k}{di_k} \quad \forall\ k \tag{27}$$

Generation 1 maximizes its utility by choosing the level of investment in insurance, i, given perfect foresight of prices in different states k:

$$\max_{i} \quad U_1 = \sum_{k} \pi_k u_1\left[e_1 - c[i] + p_k i\right] \tag{28}$$

resulting in the first order condition:

$$\sum_{k} \pi_k u_{1k}^{\prime}\left(p_k - \frac{dc}{di}\right) = 0 \tag{29}$$

With $i_k = i \; \forall \; k$, and substituting (27) into (29), the equilibrium insurance investment, i*, can be determined from:

$$\sum_{k} \pi_k u_{1k}^{\prime}\left(\frac{dd_k[i^*]}{di} + \frac{dc[i^*]}{di}\right) = \sum_{k} \pi_k u_{1k}^{\prime} \, g_k[i^*] = 0 \tag{30}$$

where $g_k[i]$ is the net marginal cost of insurance (marginal cost minus marginal benefit) in state k with:

$$g_k[i] = \frac{dd_k[i]}{di} + \frac{dc[i]}{di} \tag{31}$$

All g_k in (30) are strictly increasing in i ($d^2c/di^2 > 0$ and $d^2d_k/di^2 > 0$). Also, all $\pi_k u'_{1k}$ are positive. Hence, (30) determines i* uniquely.

3.1.2 The Coordinated Solution

Alternatively, consider that ex-ante markets were complete, and generation 2 could trade with generation 1 at time 1. Now, markets for insurance, i_k, in different states of the world are open at time 1 with prices q_k in terms of the consumption good in state A. Markets are also open for transfers in state contingent consumption goods, t_k, from generation 1 to generation 2 with prices q_{tk}. Hence, the numeraire good is the consumption good in state A. Utilities are the same as above. However, to distinguish utilities between both equilibria, they are here denoted with v instead of u. Now, generation 1 maximizes its utility by choice of investment in insurance, i, and state contingent transfers, t_k:

$$\max_{i,t_k} \quad V_1 = \pi_A v_1\left[e_1 - c[i] + \sum_{k=A} q_k i + \sum_{k=B} q_{tk} t_k\right] + \sum_{k=B} \pi_k v_1\left[e_1 - c[i] - t_k\right] \tag{32}$$

The resulting first order conditions are:

$$\begin{aligned} \pi_A v_{1A}' \sum_i q_k &= \sum_k \pi_k v_{1k}' \frac{dc}{di} \\ q_{tk} &= \frac{\pi_k v_{1k}'}{\pi_a v_{1A}'} \quad \forall\ k \end{aligned} \tag{33}$$

Generation 2 maximizes its ex-ante utility by choice of insurance acquired in each state and state contingent transfers:

$$\max_{i_k,t_k} \quad V_2 = \pi_A v_2\left[e_2 - d_k[i_k] - \sum_{k=A} q_k i_k - \sum_{k=B} q_{tk} t_k\right] + \sum_{k=B} \pi_k v_2\left[e_2 - d_k[i_k] + t_k\right] \tag{34}$$

The resulting first order conditions are:

$$\begin{aligned} q_k &= -\frac{\pi_k v_{2k}'}{\pi_A v_{2A}'} \frac{dd_k}{di_k} \quad \forall\ k \\ q_{tk} &= \frac{\pi_k v_{2k}'}{\pi_A v_{2A}'} \quad \forall\ k \end{aligned} \tag{35}$$

For all markets to clear, $i_k = i$ for all k. With (33) and (35) relative marginal utilities are equalized across generations:

$$q_{tk} = \frac{\pi_k v_{1k}'}{\pi_A v_{1A}'} = \frac{\pi_k v_{2k}'}{\pi_A v_{2A}'} \quad \forall\ k \tag{36}$$

Combining (33) and (35), the equilibrium insurance investment, i**, can be determined from:

$$\sum_k \pi_k v'_{1k}\left(\frac{dd_k[i^{**}]}{di} + \frac{dc[i^{**}]}{di}\right) = \sum_k \pi_k v'_{1k}\, g_k[i^{**}] = 0 \qquad (37)$$

Again, (37) determines i** uniquely since all g_k are strictly increasing in i and $\pi_k v'_{1k}$ are positive for all k.

3.1.3 Comparison Between Both Equilibria

Now, the relationship between equilibrium insurance with incomplete markets, i*, and with hypothetical complete markets, i**, can be analyzed by comparing equations (30) and (37). This leads to

Proposition 2.2: **The incompleteness of intergenerational insurance markets leads to inefficiently low insurance investment by generation 1 (i** > i*).**

Proof:

From (28), u_{1k} depends on the state k only through p_k. From (27), $p_k = -dd_k/di$. Insurance was defined by $A < B \Leftrightarrow dd_A/di < dd_B/di$, hence $A < B \Leftrightarrow u_{1A} > u_{1B}$ and with $u'' < 0$, $A < B \Leftrightarrow u'_{1A} < u'_{1B}$. This means given any choice of i with $i > 0$, generation 1 is worse off in good states of the world than in bad states. This is because damage does not affect generation 1 directly. However, generation 1 benefits from damage by being able to sell insurance to generation 2 at a higher price. As a result, marginal utility of generation 1 is higher in good states of the world. Now, consider the hypothetical complete market arrangement. From (36) follows that both generations' ordering of utility over states must be the same in equilibrium. Since aggregate wealth is larger in good states of the world (damage is always positive), both generations' utility must be higher in good states. Hence, $A < B \Leftrightarrow v'_{1A} > v'_{1B}$.

Equation (30) equalizes the weighted sum of the functions $g_k[i]$ with zero. For illustration, the shape of the $g_k[i]$ functions is shown in Figure 2.5 (b). Since the weights $\pi_k u'_{1k}$ are positive for all k and $A < B \Leftrightarrow g_A[i] < g_B[i]$, some $g_k[i^*]$ must be positive while others must be negative and there must be a state H such that $g_k[i^*] \leq 0$ for $k < H$ and $g_k[i^*] > 0$ for $k > H$. Now the equilibrium equations (30) and (37) are normalized by the respective marginal utilities in state H:

$$\sum_k \frac{u'_{1k}}{u'_{1H}} \pi_k \, g_k[i^*] = 0$$
$$\sum_k \frac{v'_{1k}}{v'_{1H}} \pi_k \, g_k[i^{**}] = 0 \qquad (38)$$

Now, for every $k > H$ ($g_k[i^*] > 0$), $u'_{1k}/u'_{1H} > 1$ and $v'_{1k}/v'_{1H} < 1$; also for every $k < H$ ($g_k[i^*] < 0$), $u'_{1k}/u'_{1H} < 1$ and $v'_{1k}/v'_{1H} > 1$. Hence, replacing all weights on positive g_k by a smaller number and all weights on negative g_k with a larger number, it must hold:

$$\sum_k \frac{v'_{1k}}{v'_{1H}} \pi_k \, g_k[i^*] < 0 \qquad (39)$$

Since all g_k are increasing in i, from (38) and (39) follows $i^* < i^{**}$. Since i^{**} is the unique value for i in a Pareto efficient coordinated solution, the competitive level of insurance investment, i^*, is inefficiently low.■

3.2 Building a Dam to Protect Future Generations

An other application to a hypothetical real life situation is provided to illustrate the relevance of the foregoing results. This is a somewhat more complex version of the dam-building case presented in the introduction, which allows continuous levels of insurance investments. At time 1, generation 1 can invest in building a dam that will protect generation 2 from a possible flood. The probability of a flood striking at time 2 is $1-\pi$ (state B). If the flood strikes, the damage to generation 2 is Max[d-i,0] where i is the hight of the dam built by generation 1. The cost of building the dam is linear in its hight, c[i] = c·i. If the flood does not strike (state A), there are no benefits from the dam. First consider the case without ex ante markets (competitive solution). Both generations have log-utility over the single consumption good with endowments e_1 and e_2. Generation 1's problem is:

$$\max_{i} \quad U_1 = \pi Log[e_1 + p_A i - c i] + (1-\pi) Log[e_1 + p_B i - c i] \qquad \textbf{(40)}$$

The first order condition of generation 1's maximization problem for an interior solution is:

$$\frac{(c-p_B)(\pi-1)}{e_1 - ci + ip_B} + \frac{(p_A - c)\pi}{e_1 - ci + ip_A} = 0 \qquad \textbf{(41)}$$

Generation 2's problem is:

$$\max_{i_A i_B} \quad U_2 = \pi Log[e_2 - p_a i_A] + (1-\pi) Log[e_2 - p_B i_B - d + i] \qquad \textbf{(42)}$$

The maximization of generation 2 simply fixes prices at marginal benefits (p_A = 0, p_B = 1). With these prices, (41) can be solved for i. Taking corner solutions into account, generation 1 would build a dam with hight i*:

$$i^* = Min\left[Max\left[\frac{e_1(c-1+\pi)}{c^2-c}, 0\right], d\right] \qquad \textbf{(43)}$$

Consider a numerical example with π = 0.5, d = 0.5, c = 0.5, e_1 = e_2 = 1 (see Figure 2.6). Then, the dam hight under the competitive solution is zero. In the competitive solution, utilities are U_1 = 0 and U_2 = -0.347

Consider next the coordinated solution with hypothetically complete markets at time 1. At time 1, there is trade in four goods: consumption in state A and in state B and dam hight in state A and in state B. Consumption in state A is chosen as the numeraire. Transfers of the consumption good between both states are denoted t. p_t is the payment of consumption good in state A for one unit of consumption in state B. p_A and p_B are the respective prices

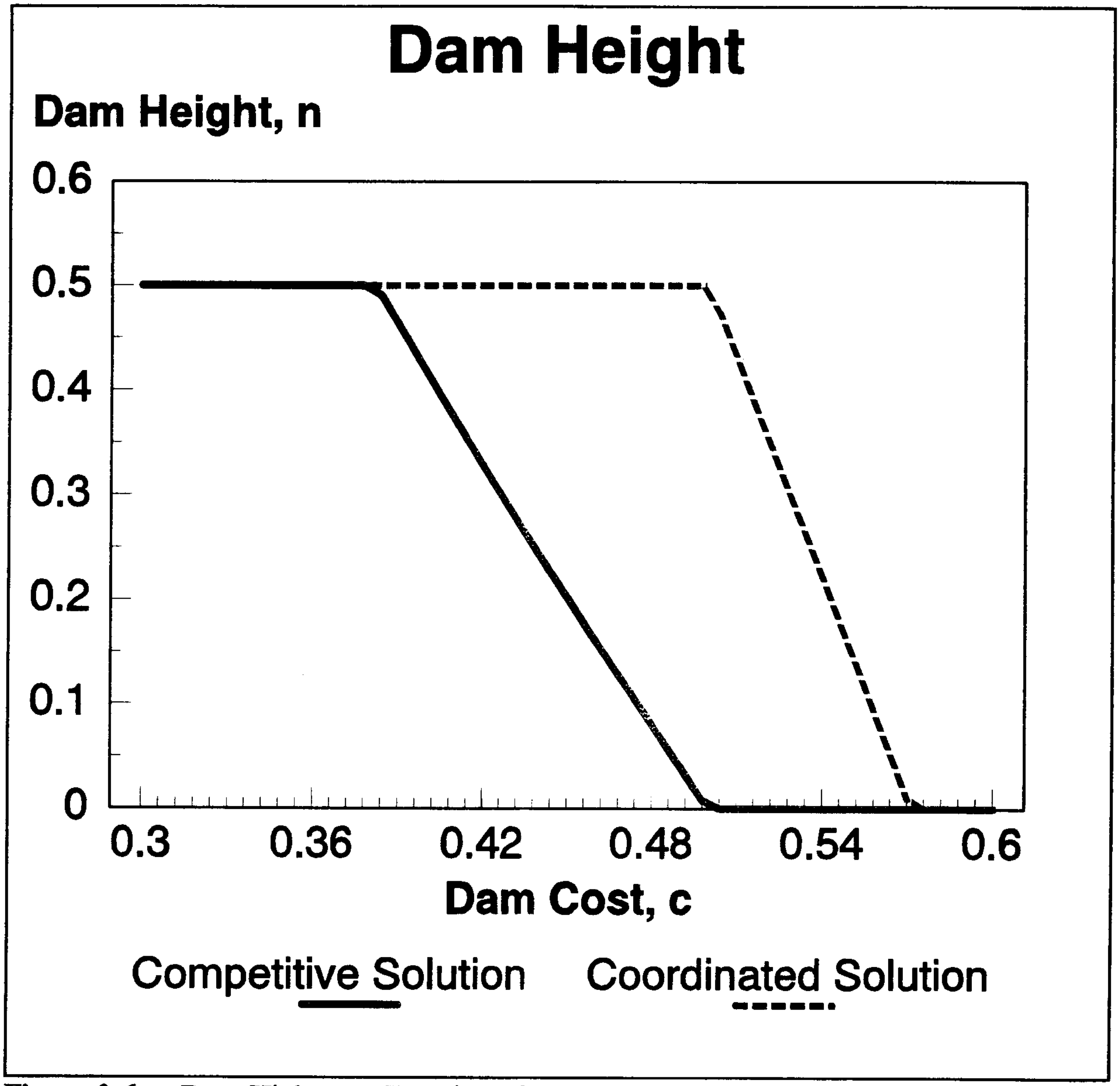

Figure 2.6 Dam Hight as a Function of Costs

per unit of the dam in terms of consumption in state A. Now, the problem of the first generations is:

$$\max_{i,t} \quad V_1 = \pi Log[e_1 - ci + (p_A + p_B)i - p_t t] + (1-\pi) Log[e_1 - ci + t] \tag{44}$$

with first order conditions:

$$\frac{c(1-\pi)}{ci-t-e_1}+\frac{(p_A+p_B-c)\pi}{e_1+i(p_A+p_B-c)-p_t t}=0$$
$$\frac{\pi-1}{e_1-ci+t}+\frac{p_t\pi}{e_1+i(p_A+p_B-c)-p_t t}=0 \tag{45}$$

The second generation's problem is:

$$\max_{i_A,i_B,t}\ V_2=\pi Log[e_2-p_A i_A-p_B i_B+p_t t]+(1-\pi)Log[e_2-d+i_B-t] \tag{46}$$

The first order conditions are (with $i_A = i_B = i$):

$$\frac{\pi-1}{e_2-d+i-t}+\frac{p_t\pi}{e_2-i(p_A+p_B)+p_t t}=0$$
$$\frac{1-\pi}{e_2-d+i-t}+\frac{p_B\pi}{i(p_A+p_B)-p_t t-e_2}=0 \tag{47}$$
$$\frac{p_A\pi}{i(p_A+p_B)-p_t t-e_2}=0$$

From the first order conditions, the dam hight in the coordinated solution, i**, can be determined as:

$$i^{**}=Min\left[Max\left[\frac{(c-1+\pi)(e_1+e_2)+cd\pi}{c^2-c},0\right],d\right] \tag{48}$$

The other equilibrium values are:

$$t=\frac{(1-c-\pi)e_1+(c-c^2-c\pi)e_2+c^2d\pi}{c-c^2}$$
$$p_A=0$$
$$p_B=\frac{c}{c-1} \tag{49}$$
$$p_t=\frac{c}{c-1}$$

For $\pi = 0.5$, d = 0.5, $e_1 = e_2 = 1$, the dam would be built at full hight (i = 0.5) and the resulting utility values would be $U_1 = 0$, $U_2 = -0.288$, which implies a Pareto improvement compared to the competitive solution. Figure 2.6 compares the dam hight in the competitive solution with the coordinated solution for a range of dam cost, c. Note that at $c = 0.5$, the marginal cost of the dam equals its expected marginal benefits. At this value, the dam would not be built under market arrangements but would be built with full hight under an efficient coordination mechanism. Also, from equations (43) and (48) follows that $i^{**} \geq i^*$ if $c < 1$ and $d \leq e_2$. These two conditions simply require that the cost of the dam be less than its benefit in the bad state and damage to generation 2 not exceed its endowment.

3.3 Conservation of Biodiversity

Next consider another simple application that shows the trade-off between diversity (insurance investment) and specialization (economies of scale). This model relates the findings of the general model to the loss of species occurring as a result of productive activities of the current generation. Again, generation 1 produces at time 1 and consumes at time 2; generation 2 is born at time 2, and produces and consumes at time 2. There is a land area of size L that is cultivated by the first generation at time 1 and by the second generation at time 2. This area is the habitat of two grain species, rice and wheat. Both grains are perfect substitutes in consumption. One unit of land yields one unit of grain whether it is cultivated with rice or wheat. At time 1, there is no uncertainty about yields. For every species that is cultivated or preserved without cultivation, there is a setup-cost $s \leq L/2$, expressed in land area that has to be set aside, i.e., for seed development or research. If a species is not cultivated, or preserved on an area of size s, it becomes extinct. Without considering generation 2, generation 1 has no benefits from diversity. It would grow only one of the two species and let the other one become extinct.

At time 2, generation 2 is born into one of two states. For example due to a pest or a change in climate, wheat does not grow in state A, and rice does not grow in state B. The seeds for the species that was cultivated by generation 1 are passed on to generation 2 for free. However, if generation 1 cultivated only the crop that does not grow in the state into which generation 2 is born, generation 2 would be willing to buy the seeds for the other

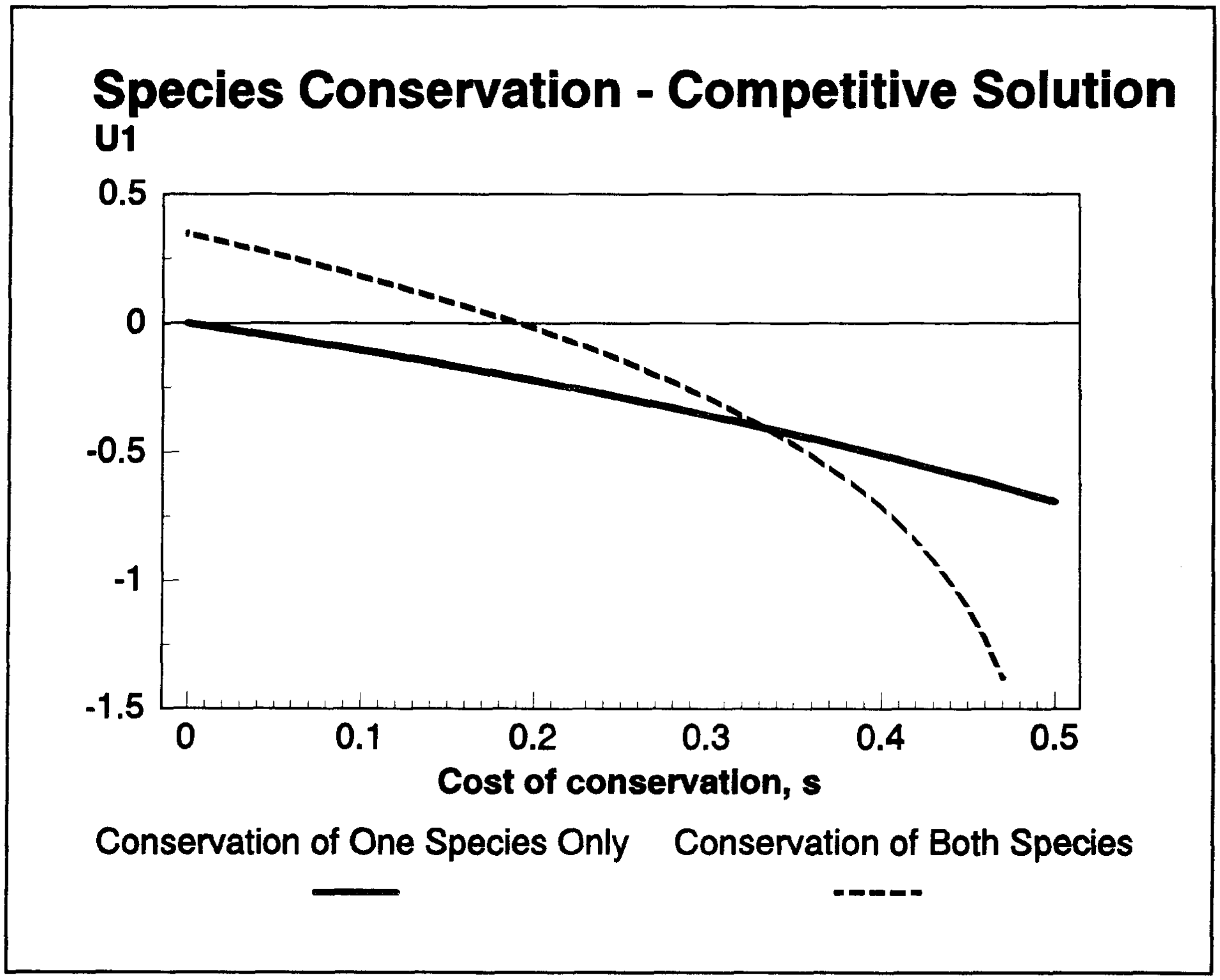

Figure 2.7 The Conservation of Species and Welfare of Generation 1

species from generation 1 at any price below L. Anticipating this at time 1, generation 1 compares its welfare, U_1, between conserving one and two species, considering the cost of preserving the second species, s. Both states are equally probable; both generations have log-utility and consume grain only. Let g denote the number of species preserved ($g \in \{1,2\}$). Then, generation 1 faces the problem:

$$\max_{g\in\{1,2\}} \; U_1 = 0.5\,Log[L-gs] + 0.5\,Log[g(L-s)] \tag{50}$$

With L = 1, generation 1 would conserve the second species in the competitive solution only if $s < 1/3$ as shown in Figure 2.7. However, if ex-ante contracting was allowed, generation

2 would commit itself to paying up to L in both states for the conservation of the second species in order to avoid starvation in the bad state.

To see the Pareto improvement resulting from inter-generational coordination, consider the following numerical example. With $L=1$, $s=1/3+\epsilon$ and $\pi=0.5$, generation 1 will grow only one species and receive utility $U_1 = \text{Log}[L\text{-}s] = -0.405$. Generation 2 would starve in the bad state and hence receive utility $U_2 = 0.5\cdot\text{Log}[L]+0.5\cdot\text{Log}[0] = -\infty$. With an agreed price for the conservation of the second species between 1/3 and 1 in both states, both generations could be made better off. Assume a price for conservation of 0.4. Now, $U_1 = \text{Log}[L\text{-}2s+0.4] = -0.310$ and $U_2 = \text{Log}[L\text{-}0.4] = -0.511$, which implies a Pareto improvement over the competitive solution. Hence, the incompleteness of inter-generational markets would have led to the inefficient extinction of one of the two species in the competitive solution. The extinction of a species is an irreversible decision that is associated with the loss of an option value (see Arrow and Fisher 1974 and Pindyck 1991). This option value is implicit in the above maximization problem of generation 1 and is lower under incomplete markets than under an efficient coordination mechanism.

3.4 Consumption of a Non-Renewable Resource

In this application, the implications of incomplete inter-generational insurance markets for the depletion of a non-renewable resource are analyzed for the case of uncertainty about the resource stock. Consider the simplest possible model with two generations, 1 and 2, two states, A and B, and a single consumption good, which is the non-renewable resource. There is no production in this economy. Generation 1 lives and consumes at times 1 and 2; generation 2 lives and consumes at time 2 only. The endowments of both generations depend on the state that is revealed at time 2. These endowments are denoted e_{1A}, e_{1B}, e_{2A} and e_{2B}. At time 1, generation 1 may consume up to the minimum of e_{1A} and e_{1B} ($c_{11} \leq \min[e_{1A},e_{1B}]$). The competitive solution does not include any trade opportunities since within each state there is only one good, and trade across states is impossible since generation 2 is born into one of the two states. Hence, generation 2 simply consumes its endowment in the respective state. Generation 1 chooses its consumption at time 1 by maximizing its utility, U_1:

$$\max_{c_{11}} \quad U_1 = u_{11}[c_{11}] + \pi u_{12}[e_{1A} - c_{11}] + (1-\pi) u_{12}[e_{1B} - c_{11}] \tag{51}$$

(with u' > 0 and u'' < 0) resulting in the first order condition:

$$u/_{11} = \pi u/_{1A} + (1-\pi) u/_{1B} \tag{52}$$

Clearly, the competitive solution is inefficient if the resulting risks of both generations differ, that is if:

$$\frac{u'_{1A}[e_{1A} - c^*_{11}]}{u'_{1B}[e_{1B} - c^*_{11}]} \neq \frac{u'_{2A}[e_{2A}]}{u'_{2B}[e_{2B}]} \tag{53}$$

where c^*_{11} is the utility maximizing consumption of the resource at time 1 in the competitive solution.

To find the efficient solution, hypothetical ex-ante trade across states is introduced. Both generations now maximize their respective utilities by choice of trade across states. Let t denote the amount of the resource sold (bought) by generation 1 (generation 2) in state B against payment of resources in state A. Let p denote the price of the resource in state B in terms of the resource in state A. Utilities in the coordinated solution are denoted by v. Then the maximization problems are:

$$\begin{aligned} \max_{c_{11},t} \quad & V_1 = v_{11}[c_{11}] + \pi v_{12}[e_{1A} - c_{11} - pt] + (1-\pi) v_{12}[e_{1B} - c_{11} + t] \\ \max_{t} \quad & V_2 = \pi v_2[e_{2A} + pt] + (1-\pi) v_2[e_{2B} - t] \end{aligned} \tag{54}$$

After p is eliminated from the resulting three first order conditions, the coordinated solution is determined by the following two equations:

$$\frac{v'_{1A}}{v'_{1B}} = \frac{v'_{2A}}{v'_{2B}} \tag{55}$$

$$v'_{11} = \pi v'_{1A} + (1-\pi) v'_{1B}$$

Now, two questions can be analyzed. First, given any choice of c_{11}, how does the sharing of resources at time 2 change between the competitive and the coordinated solution; and second, how does c_{11} compare between both solutions. The first question is answered by the first equation in (55). If the competitive solution leads to different risks across generations, (53), trade would equalize these risks. Hence, if generation 2 faces larger endowment risk than generation 1, generation 1 would take on some of this risk in the coordinated solution, and vice versa.

The second question of the effect of trade on c_{11} is more complex and addresses inefficiencies in the aggregate resource depletion path that may arise due to the market incompleteness. Recall that, in the insurance model in section 2.3, it was possible for generation 1 to simultaneously increase insurance investment and increase consumption at time 1. Therefore, unambiguous under-insurance results could be obtained. In the resource depletion case, generation 1 cannot invest for one state only. It can only postpone resource consumption (reduce c_{11}), which increases its wealth in both states equally. Reducing c_{11} has an insurance effect since leaving more of the resource behind reduces aggregate uncertainty at time 2. However, since trade at time 2 makes generation 1 better off, there is an additional income effect that would tend to increase c_{11} if consumption at time 1 is a normal good. Since the insurance and income effect are working in opposite directions, the aggregate impact of opening trade on c_{11} is ambiguous. Because of the importance of understanding the impact of incomplete markets on the resource depletion path, the aggregate effect will be explored in more detail in this section.

For the following analysis, $\pi = 0.5$ is assumed to simplify notation. A is considered the bad state ($e_{1A} < e_{1B}$). Also, in the competitive solution, generation 2 faces higher uncertainty than generation 1 ($u'_{1A}/u'_{1B} < u'_{2A}/u'_{2B}$). These assumptions would reflect a realistic setting in which the current generations faces some endowment uncertainty about the resource stock, and future generations face higher uncertainty in the same direction. Hence, if trade between both generations across states was allowed, generation 1 would sell resource in the bad state, A, for resource in the good state, B. First, there is the price, or insurance, effect of allowing trade across states on c_{11}. Let p be the price of the resource in state B in terms of the resource in state A. Then, the relative price of c_{11} is the sum of the resource prices in both states, divided by the value of generation 1's endowment, $(1+p)/(e_{1A}+p\cdot e_{1B})$. Trade leads to a price, p, that is lower than the price implicit in the no-trade solution. With $e_{1A} < e_{1B}$, the relative price of consumption at time 1 increases with a decrease in p. Hence, trade increases the relative price of consumption at time 1, and the price, or insurance, effect of allowing trade would lead to a reduction of c_{11}. Second, however, trade leads to higher welfare. The resulting income effect would tend to increase c_{11}. The net effect of opening markets on c_{11} depends on the curvature of the utility function.

The illustration in Figure 2.8 shows generation 1's indifference map for resource consumption at time 2 with the optimal resource consumption in states A and B, c^*_{1A} and c^*_{1B}, for the competitive solution assumed to be at point E ($c^*_{1A} = 1$, $c^*_{1B} = 2$). The implicit price at this no-trade equilibrium is determined by the ratio of marginal utilities (shown by the price line $p = 0.5$). If markets across states were opened, an explicit price would be formed below $p = 0.5$ (since generation 2's resource endowment is assumed to be more risky than that of generation 1). Generation 1 would trade from point E along the new price line to the new utility maximizing consumption point, which is the tangent of the new price line through E with an indifference curve. Two such points are shown as F and G. The offer curve shown in Figure 2.8 is the line connecting the utility maximizing consumption choices of generation 1 for all possible equilibrium prices. The impact of trade on c_{11} is determined by the change of expected marginal utility of resource consumption at time 2 that occurs because of allowing trade across states (compare equations (52) and (55)). If, for a given c_{11}, trade leads to a rise in expected marginal utility from consumption at time 2, c_{11} will decline, and vice versa. Hence the expected marginal utility at the competitive solution (point E) needs to be compared to the trade equilibrium (on the offer curve). Note that the

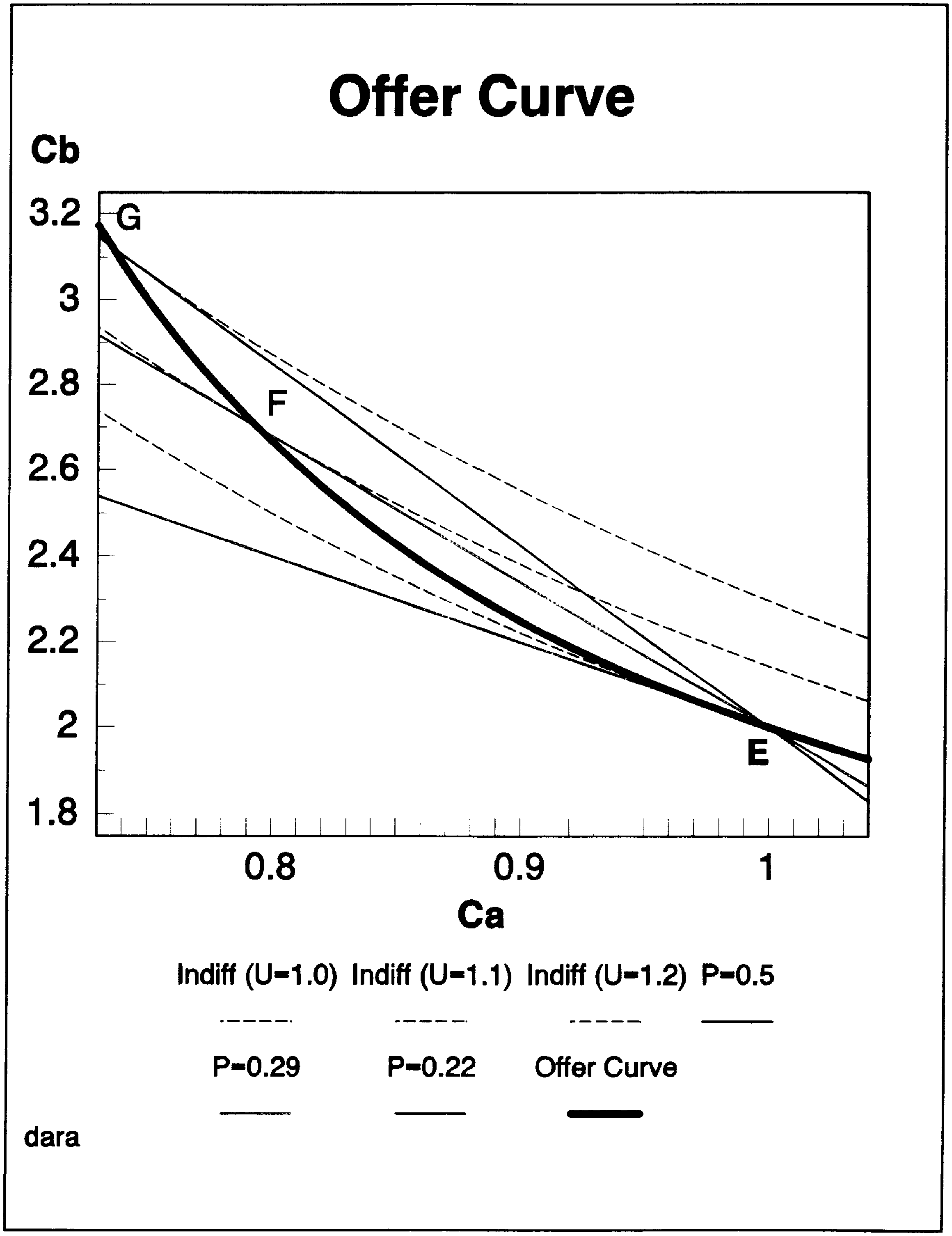

Figure 2.8 Offer Curve

trade equilibrium is not necessarily the coordinated solution since c_{11} may change in the competitive solution. The result of the analysis is summarized in

Proposition 3.3: **If generation 1 has increasing or constant absolute risk aversion, and generation 2 faces higher endowment uncertainty than generation 1, incompleteness of intergenerational insurance markets leads to inefficiently low resource consumption at time 1. If generation 1 has decreasing absolute risk aversion, resource consumption at time 1 can be inefficiently high.**

Proof:

Let c^*_{1A} and c^*_{1B} denote consumption in the competitive solution and c_{1A} and c_{1B} consumption choices if trade across generation was allowed, given choice of consumption at time 1 in the competitive solution, c^*_{11}. Then, $c_{1A} < c^*_{1A} < c^*_{1B} < c_{1B}$. Also $c_{1A} = c^*_{1A} - p \cdot t$ and $c_{1B} = c^*_{1B} + t$. Hence:

$$p = \frac{c^*_{1A} - c_{1A}}{c_{1B} - c^*_{1B}} \tag{56}$$

First consider increasing or constant absolute risk aversion of generation 1:

$$\frac{d\left(-\frac{u''(c)}{u'(c)}\right)}{dc} \geq 0 \quad \forall\, c \tag{57}$$

With $c_{1A} < c_{1B}$, we can write:

$$-\frac{u''(c_{1A})}{u'(c_{1A})} \leq -\frac{u''(c_{1B})}{u'(c_{1B})} \Leftrightarrow \frac{u''(c_{1A})}{u''(c_{1B})} \leq \frac{u'(c_{1A})}{u'(c_{1B})} \tag{58}$$

Utility maximization by generation 1 implies:

$$\frac{u'(c_{1A})}{u'(c_{1B})} = \frac{1}{p} \tag{59}$$

Using this and (56):

$$\frac{u''(c_{1A})}{u''(c_{1B})} \leq \frac{c_{1B} - c^*_{1B}}{c^*_{1A} - c_{1A}} \leftrightarrow u''(c_{1A})(c^*_{1A} - c_{1A}) \geq u''(c_{1B})(c_{1B} - c^*_{1B}) \tag{60}$$

With $u''<0$ and $c_{1A} < c^*_{1A} < c^*_{1B} < c_{1B}$:

$$\begin{gathered} u'(c^*_{1A}) - u'(c_{1A}) > u''(c_{1A})(c^*_{1A} - c_{1A}) \\ u''(c_{1B})(c_{1B} - c^*_{1B}) > u'(c_{1B}) - u'(c^*_{1B}) \end{gathered} \tag{61}$$

Combining (60) and (61), therefore:

$$u'(c^*_{1A}) + u'(c^*_{1B}) > u'(c_{1A}) + u'(c_{1B}) \tag{62}$$

Since trade leads to a lower expected marginal utility from consumption at time 2, the efficient coordinated solution implies higher consumption at time 1 than the competitive solution: $c_{11}^{**} > c_{11}^{*}$, where c_{11}^{**} is the (efficient) resource consumption at time 1 in the coordinated solution.

Next consider decreasing absolute risk aversion. In addition, an assumption is made that the decrease in absolute risk aversion is large compared to the price change brought about by trade. This assumption is:

$$\frac{-\frac{u''(c^*_{1A})}{u'(c^*_{1A})}}{-\frac{u''(c^*_{1B})}{u'(c^*_{1B})}} > \frac{\frac{u'(c^*_{1B})}{u'(c^*_{1A})}}{p} \tag{63}$$

Note that the RHS of (63) is the implicit price of the resource in state B in the competitive no-trade solution divided by p, the price with trade. Since the price is lower with trade, the

RHS is greater than one. The LHS is greater than one because of decreasing absolute risk aversion. However, the additional assumption is made that the LHS is greater than the RHS. Rearranging (63), and using (56):

$$\frac{u''(c_{1A}^*)}{u''(c_{1B}^*)} > \frac{c_{1B}-c_{1B}^*}{c_{1A}^*-c_{1A}} \Leftrightarrow u''(c_{1A}^*)(c_{1A}^*-c_{1A}) < u''(c_{1B}^*)(c_{1B}-c_{1B}^*) \tag{64}$$

With $u''<0$ and $c_{1A} < c^*_{1A} < c^*_{1B} < c_{1B}$:

$$\begin{aligned} u'(c_{1A}^*)-u'(c_{1A}) &< u''(c_{1A}^*)(c_{1A}^*-c_{1A}) \\ u''(c_{1B}^*)(c_{1B}-c_{1B}^*) &< u'(c_{1B})-u'(c_{1B}^*) \end{aligned} \tag{65}$$

Combing (64) and (65), therefore:

$$u'(c_{1A}^*)+u'(c_{1B}^*) < u'(c_{1A})+u'(c_{1B}) \tag{66}$$

Since trade leads to a higher expected marginal utility from consumption at time 2, the efficient coordinated solution implies lower consumption at time 1 than the competitive solution: $c_{11}^{**} < c_{11}^*$. There is inefficient over-consumption in the competitive solution.■

Now consider examples for both cases (over- and under-consumption of resources at time 1). In order to analyze the change in expected marginal utility between the no-trade equilibrium, E, and another point on the offer curve, the iso-expected marginal utility (IEMU) curve is introduced. This is a curve connecting all points in the consumption space of generation 1 at time 2 that result in the same expected marginal utility as point E. The position of the IEMU curve depends on whether the utility function shows decreasing, constant, or increasing absolute risk aversion. In the simplest case of constant absolute risk aversion (CARA: $d(-u''/u')/dc = 0$, i.e., exponential utility), the IEMU curve lies exactly on the indifference curve through E since any change in utility is accompanied by a proportional change in marginal utility. Since the offer curve is tangent to the indifference curve in E and lies above the indifference curve anywhere else (voluntary trade must make generation 1 better off), trade must results in a point above the IEMU curve. This implies lower IEMU from consumption at time 2 and, hence, higher c_{11} than in the competitive solution.

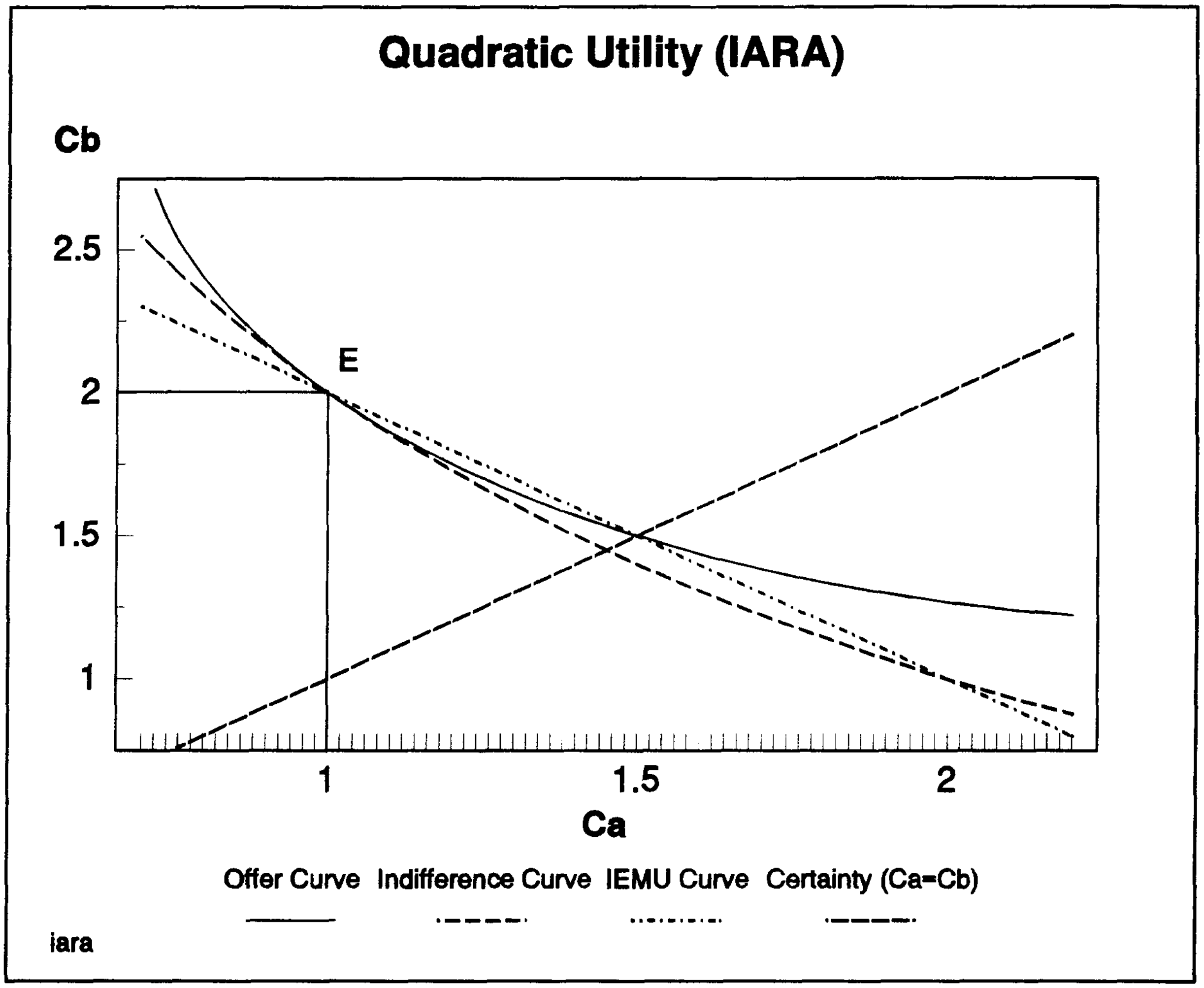

Figure 2.9 Resource Depletion with Quadratic Utility

As an example of increasing absolute risk aversion (IARA: d(-u''/u')/dc > 0), quadratic utility is shown in Figure 2.9. Moving along an indifference curve away from the certainty line, expected marginal utility increases with IARA utility; hence, the IEMU curve is flatter than the indifference curve when $c_B > c_A$ and steeper when $c_B < c_A$. Here, to the left of the competitive solution, E, in Figure 2.9, the IEMU curve must lie below the indifference curve and the offer curve above the indifference curve. Hence, whenever generation 2 faces higher endowment risk than generation 1, generation 1 will inefficiently under-consume the resource at time 1. As can be seen from Figure 2.9, the impact of trade on c_{11} is ambiguous if generation 1 faces higher endowment uncertainty than generation 2 (to the right of E).

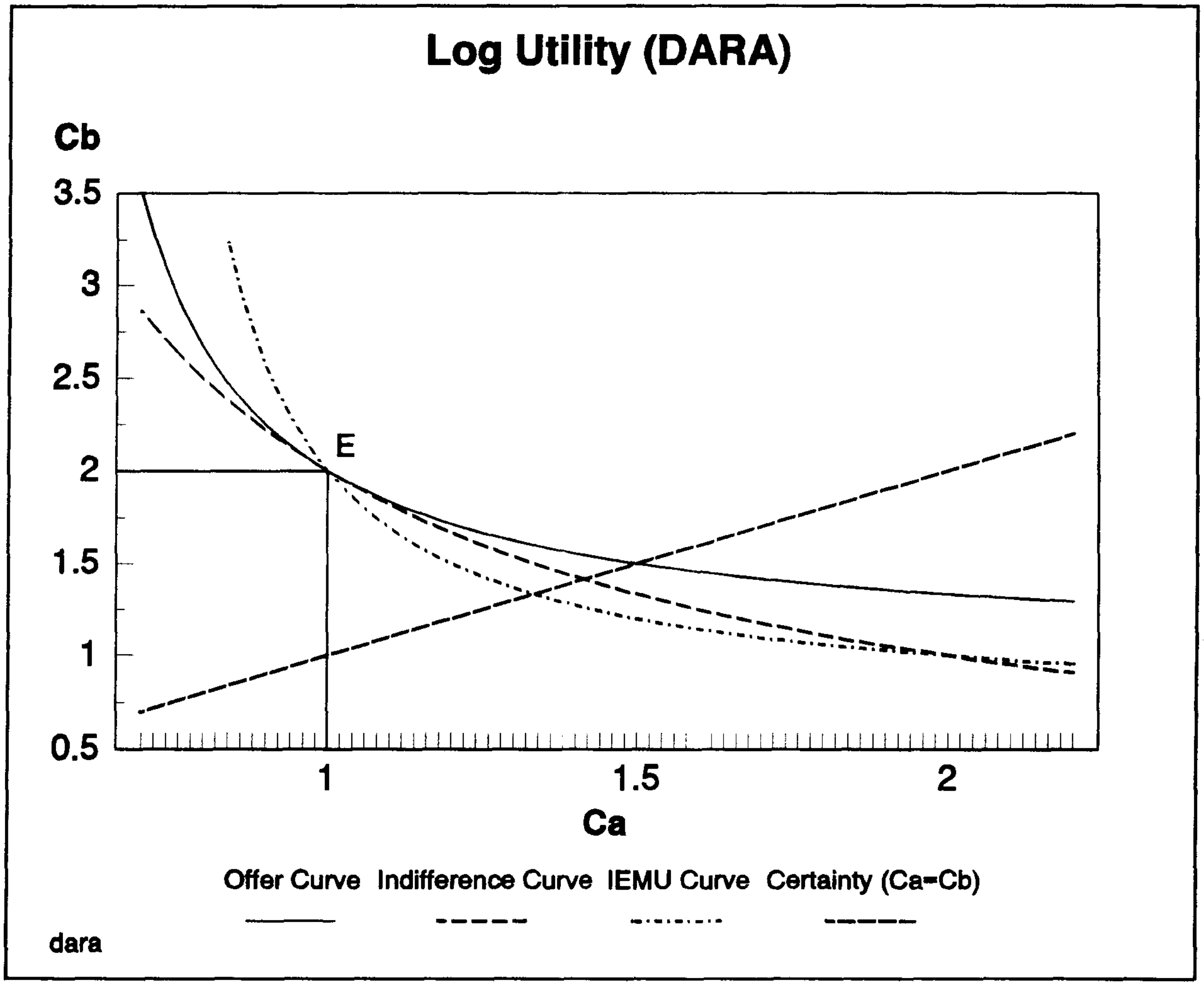

Figure 2.10 Resource Depletion with Log-Utility

Decreasing absolute risk aversion (DARA) is intuitively more appealing.[2] An example of DARA (log-utility) is shown in Figure 2.10. With DARA utility, the IEMU

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[2] Arrow (1970) shows that decreasing absolute risk aversion implies that the risky asset is a normal good, i.e., the demand for risky assets increases with an increase in an individual's wealth.

curve is steeper than the indifference curve when $c_B > c_A$ and flatter when $c_B < c_A$. Since the offer curve is tangent to the indifference curve in E, the offer curve must lie beneath the IEMU curve at least for some range to the left of E. Hence, in this area, incompleteness of markets leads to excessive resource consumption at time 1.

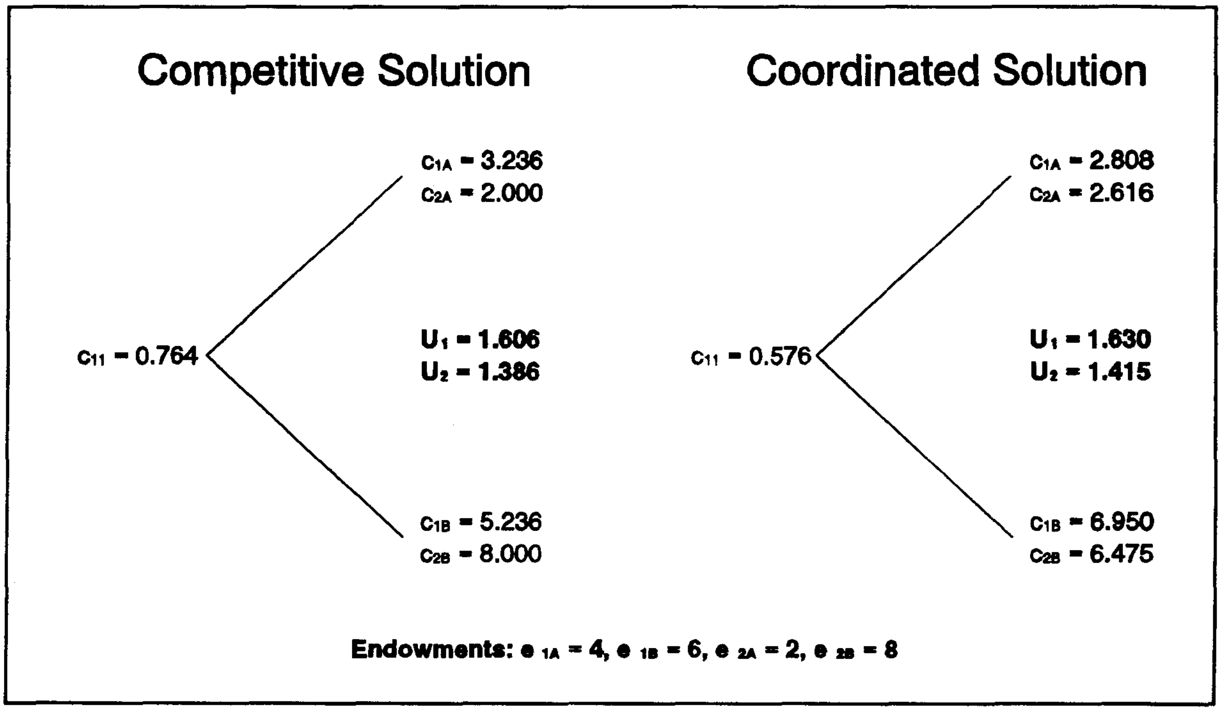

Figure 2.11 Over-Consumption of a Non-renewable Resource

A numerical example will illustrate the over-consumption problem resulting from higher endowment risk of the second generation under log-utility. Assume utility functions:[3]

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3 Consumption at time 1 enters the utility function linearly in order to obtain a simple explicit solution. This functional form is not required for obtaining the over-consumption result.

$$U_1 = \frac{c_{11}}{4} + 0.5\,Log[c_{1A}] + 0.5\,Log[c_{1B}]$$
$$U_2 = 0.5\,Log[c_{2A}] + 0.5\,Log[c_{2B}] \quad (67)$$

and endowments $e_{1A} = 4$, $e_{1B} = 6$, $e_{2A} = 2$, $e_{2B} = 8$. In the competitive solution $c^*_{11} = 0.764$. This results in $u'_{1A}/u'_{1B} = 1.62 < u'_{2A}/u'_{2B} = 2$. Since the risk faced by generation 2 is greater, this implies over-consumption. Consumption in the coordinated solution would only be $c^{**}_{11} = 0.576$. The over-consumption in the competitive solution and the Pareto improvement through the coordinated solution are confirmed by the equilibrium values for this example shown in Figure 2.11. The intuition for the dependence of the over-consumption result on decreasing risk aversion is that generation 1 assumes a risk by not consuming the resource at time 1 since the value of the resource at time 2 is uncertain. Since trade increases generation 1's wealth (in utility terms), decreasing risk aversion leads to a higher willingness to take on the risk of postponing consumption, and hence lower resource consumption at time 1 in the trade case (coordinated solution).

4 Conclusions

This chapter has shown that the incompleteness of intergenerational insurance markets constitutes a market failure that leads to inefficient intergenerational investment decisions under risk. Early generations over-diversify if they face risks that are larger than those of the following generation and could, therefore, be shared across generations. On the other hand, if risks are increasing from generation to generation, the current generation would under-insure against those risks. Furthermore, a generation with decreasing absolute risk aversion would, in many cases, over-consume a natural resource if the stock uncertainty is larger for future generations. The main message of this chapter is caution against the belief that markets work efficiently to transmit across generations the right signals for economic decisions under risk. The larger the social risks involved, the more reason is there to believe that markets do not bring about efficient decision making by the current generation. The direction of the inefficiency, however, depends on the nature of the risk assumed. Therefore, the policy implications that can be drawn from this chapter depend on the empirical assessment of the risks that the current and future generations are facing.

For many types of natural capital depletion (i.e., resource depletion, reduction of biodiversity, large-scale emissions), short-term effects are minor compared to possible, but uncertain, future effects. Hence, natural capital depletion would generate risks that fit the pattern of those risks which would be inefficiently under-insured by market forces. Therefore, the effect of under-insurance of future risks and over-consumption of resources appears to be empirically more relevant for environmental problems than the over-diversification result. Many global environmental issues involve large-scale and long-term uncertainties that would lead to under-insurance. The uncertain costs of global warming, ozone layer depletion and land degradation would be expected to increase with time and, hence, fall into the category of risks that would be under-insured through competitive markets. With respect to global warming, note that a reduction in the release of greenhouse gases itself does not fall into this category since such an insurance policy impacts on future generations through an intergenerational externality and not through markets. Greenhouse gas emissions are inefficiently high due to the external costs such emissions create. However, this chapter shows that there is not only an inefficiently high incentive to release greenhouse gases but also an inefficiently low incentive to undertake protective measures against the consequences of the greenhouse effect, even if such insurance could be sold to future generations.

Another application with policy relevance is the preservation of biodiversity. Through the required preservation of habitat, it is costly to conserve a species. If there are no or only small expected benefits from a species during the lifetime of the current generation but larger uncertain benefits to future generations, current generations would have an inefficiently low incentive to make the investments required to conserve biodiversity. Similarly, long-term investment in back-stop technologies for the provision of energy (i.e. solar energy technologies) would be inefficiently low. Many other examples would involve irreversible activities (such as land conversion) that generate uncertain opportunity costs that are expected to arise only after the lifetime of the current generation.

The results of this chapter suggest that in all these situations, an intergenerational coordination mechanism could lead to gains for all generations. Such intergenerational coordination mechanism would link the relative risks of generations, and would require later generations to compensate earlier generations for insurance investments even if the bad state does not occur and insurance is worthless, ex-post. A possible coordination mechanism could involve debt contracts that create obligations for future generations to pay for insurance investments of earlier generations even if the investment turns out to be worthless in the particular state that is realized. A sustainability constraint on the activities of the current generation, as an alternative coordination mechanism, will be discussed in chapter IV. A sustainability constraint would commit the current generation to ensure consumption possibilities of future generations equal to the current generation's consumption. A sustainability constraint would require higher provisions for future generations if they are born into a bad state of the world, and vice versa, and, thus, link relative risks across generations.

CHAPTER III

ENVIRONMENTAL DECISION MAKING UNDER AMBIGUITY AND IGNORANCE

1 Introduction

The standard model for decision making under uncertainty is the expected utility model, either with objective probabilities (von Neumann and Morgenstern 1947) or extended to subjective probabilities (Savage 1954) over states of the world. In expected utility theory, uncertainty is modeled as risk. Risk is defined as a situation of uncertainty with a single probability distribution over a well defined set of states of the world. Hence, both approaches to expected utility require that all possible states of the world and their consequences under any of the alternative actions be known. Also, expected utility theory requires that additive probabilities can be assigned to all states. Ambiguity is a situation in which it is impossible to assign a single probability distribution to all states of the world. Ignorance is a situations in which it is impossible to describe all states of the world completely. This chapter is motivated by the belief that, by abstracting from ambiguity and ignorance, subjective expected utility theory (SEU) assumes away critical aspects of many environmental decision making problems. It is argued that, since SEU is not applicable to situations of ambiguity and ignorance, it has significant limitations as a normative model for environmental decision making.

Environmental decision making involves choices about the depletion of natural capital, i.e., choices about resource depletion, emissions, land use, and other issues. Many of these choices involve large uncertainties that are not well captured by modeling them as risk. Ambiguity and ignorance are of relevance in many environmental problems, such as global warming, ozone layer depletion and the reduction of biodiversity, which are large in scale and could potentially lead to significant changes in social welfare. Ignorance and ambiguity are important in environmental decision making because of our incomplete knowledge of the functioning of natural systems, the long lag between the time a decision is taken and the time all impacts will be felt, and the fact that many environmental effects are external to the agents making the decisions, which reduces their economic incentives for research into the consequences of their activities.

In addition to the conceptual concerns about using SEU for environmental decision making, there are practical reasons for the desire to find a more suitable model for decision making under uncertainty. Deficiencies in the practical evaluation of uncertain costs and benefits in the context of environmental decision making are widespread. The treatment of uncertain environmental costs and benefits in the cost-benefit analyses of several recent World Bank projects is examined in von Amsberg (1993). This examination shows a surprising lack of sophistication in the analysis of uncertainty. In fact, uncertain environmental costs or benefits are often excluded from the analysis completely. In particular, the costs of resource depletion, land use, habitat destruction and emissions are frequently ignored, sometimes with the explicit justification of excessive uncertainty about these costs. For example, none of the analyzed energy projects attempts to quantify the possible damages resulting from global warming and carbon dioxide emissions. Such treatment of uncertainty can clearly lead to a systematic bias in the evaluation of projects at the cost of excessive environmental destruction. One reason for these deficiencies can be found in the absence of widely accepted models that allow the representation of ambiguity, or vague uncertainties. The present chapter is motivated by these deficiencies and the importance of providing environmental policy makers with more applicable tools for the evaluation of uncertain environmental costs and benefits.

The focus of this chapter is the review of several models of decision making under uncertainty and the proposal of a model that is more suitable for normative environmental decision making than SEU. The focus of the chapter is not the development of a new theory. Rather, the purpose is to analyze existing models and combine elements of those models in order to provide a decision theory that is of practical use for environmental decision making. Section 2 will introduce the formal notation of uncertainty and discuss the requirements for a useful normative model for environmental decision making. Section 3 will review and analyze several existing decision theories. It begins with an analysis of the conceptual and practical problems of using SEU and reviews several relevant alternative models of decision making under ambiguity and ignorance. Section 4 suggests a decision making model based on a combination of the Dempster-Shafer belief-function theory and Choquet expected utility as the most suitable approach from a policy perspective. The proposed theory is illustrated by means of an example. The implications of using this model for environmental decision making are discussed. In order to focus the discussion on the problems of uncertainty in environmental decision making, this chapter abstracts from other problems of evaluating environmental costs and, such as the need to shadow price external effects, to take into account intergenerational equity effects and to choose the appropriate social discount rate for future costs and benefits.

2 Environmental Decision Making: Models and Reality

Many environmental decision making problems are highly complex. Therefore, in order to analyze a problem with limited cognitive capacities, we have to build a model of the decision making situation, which we then analyze. A model is an abstraction from reality and is supposed to reduce the analysis to those aspects of reality that are relevant for a given problem. Of course, what aspects of reality are relevant for a specific problem depends on the nature of that problem. When a new class of problems arises it is useful to examine whether the models used for other classes of problems are still the most useful abstraction of reality for the given purpose. Subjective expected utility theory (SEU) is so widely used as a tool for decision making under uncertainty that it is often forgotten that the elements of this theory are only an abstraction of reality and not reality itself. The analysis in this chapter is driven by concerns that SEU may not be a very useful model for large-scale environmental decision making. The present section lays the groundwork for analyzing this question. First, common elements and notations for decision theories will be introduced. Second, some important aspects of the reality of environmental decision making problems are discussed. Third, a list of requirements for a good model of environmental decision making is suggested.

2.1 Building Blocks of Decision Theory

In this sub-section, some building blocks of theories for decision making under uncertainty are introduced, together with some notation to be used throughout the chapter. The discussed elements are models of beliefs, acts, and values, as well as the basis for deriving normative statements from decision models. Beliefs represent the assessment of those aspects of the world that cannot be influenced by the decision maker. Beliefs are modeled by defining a list of possible states of the world and expressing the likelihood of occurrence of these states. There is a set of states of the world, $\Omega = \{\omega_1,\ldots\omega_N\}$. Each state of the world, ω, is a complete description of all relevant aspects of the world. Sometimes it is convenient to consider a partition, f, of Ω. A partition is a set of disjoint subsets of Ω, that together exhaust Ω. The elements of a partition are called events. If it is said that an event occurred, this means that information is received that the true state is one of the states contained in this element of the partition. There is a measure p on Ω that reflects beliefs in the likelihood of the states in Ω. Those aspects of the world that can be influenced by the decision maker are modeled as a set of acts, $A = \{a_1,\ldots,a_M\}$, which describe the objects of choice. The acts, a, map the states, ω, into a description of outcomes, $a(\omega)$. Finally, the decision maker holds values about different outcomes of the world and their likelihood of occurrence. These values, or preferences, held by the decision maker are modeled by a value function, $u(a(\omega),p(\omega))$, that maps acts and measures into real numbers. This value function can be used to scale the acts, a. If values, or preferences, meet some basic consistency conditions, which are assumed here, they can be expressed as a real-valued, continuous utility function (see Varian 1978, p. 113).

Consider the example of a decision about the level of emissions of a toxic chemical. The acts, or objects of choice, would be the possible levels of emissions. The states of the world would be complete descriptions of the world that determine the possible impacts of different emission levels, i.e. health impacts, damages to buildings, climatic changes, and so on. The function $a(\omega)$ describes the impacts of emission level a if state ω is the true state of the world. Finally, the value function, $u(a(\omega),p(\omega))$, would evaluate the physical impacts of different emission levels, and assign to them a level of utility or welfare, which can be used to scale the different emission levels a. The decision maker would chose the level of emissions, a, for which $u(a(\omega),p(\omega))$ is highest.

The most commonly modeled type of uncertainty is <u>risk</u>. The term risk implies assumptions in addition to the structure discussed so far. First, the decision maker is assumed to know all states of the world (know all possible complete descriptions of the world). Second, p is assumed to be a single probability measure, $\pi(\Omega)$, over the set of states, Ω, that reflects all relevant information about beliefs in the true state. This means, $\pi(\Omega)$ must fulfil the axioms of probability ($0 \leq \pi \leq 1$; $\pi(\Omega) = 1$; $\pi(A) + \pi(B) = \pi(A \cup B)$ $\forall$ $A,B \subset \Omega$ with $A \cap B = \emptyset$). Concerns about the insufficiency of modeling uncertainty as risk go back at least to Knight (1921) and Keynes (1921). Knight introduced the distinction between risk, when probabilities are known, and uncertainty, when they are not known. Keynes discussed the distinction between implications and weight of evidence. He considered the implications of evidence as leading to a probability judgement and the weight of evidence leading to a particular degree of confidence in this probability judgement. The distinction between the implications of evidence and the weight of evidence could be related, for example, to an expert's probability assessment versus the presumed reliability of the expert in making this assessment.

Extensions of risk can be captured by the terms "ambiguity" and "ignorance". <u>Ambiguity</u> describes a situation in which the decision maker knows all states of the world but p does not need to be a single probability measure; i.e., p can be a non-additive measure or a set of additive probabilities measures. <u>Ignorance</u> describes a situations in which the decision maker does not know some or all relevant states of the world. Consider the set of well defined states, Ω, as a subset of all states, Ω^* ($\Omega \subseteq \Omega^*$). Then $\Omega^* \backslash \Omega = \{\omega^*_1,\ldots,\omega^*_L\}$

is the set of states that are not well defined and will be called scenarios. A situation of ignorance is characterized by $\Omega^*\setminus\Omega \neq \emptyset$. A scenario may consist of an incomplete description of the world or a state about which no information at all is available. With a real-valued utility function it is implicitly assumed that every state of the world results in a well defined level of utility expressed in a real number. Even if a state is not completely defined, utility resulting from it is defined. Information about a scenario is assumed to be expressed as the interval of minimum and maximum utility values from this scenario. These utility values are denoted, $u_{min}(a(\omega^*))$ and $u_{max}(a(\omega^*))$. If no information at all is available about a scenario, this interval would include the lowest and highest utility values possible, i.e. minus and plus infinity. Finally, complete ignorance describes a situation in which neither a set of well known states, Ω, nor a measure, p, exist. Under complete ignorance, each act, a, is associated only with minimum and maximum utility, $u_{min}(a)$ and $u_{max}(a)$.

The concern of this chapter is how to make good environmental decisions (normative or prescriptive) rather than how to describe real life environmental decision making (positive or descriptive). Hence, the question arises how the discussed elements of decision models can be combined into a normative theory. The utility of individuals as revealed through preferences is generally accepted as the source of value and the basis for normative judgements in economics and related disciplines (see Sen 1982a). Moreover, preferences are often assumed to be stable, exogenous to individual choices, and known with adequate precision (see March 1981). While there are reasons to question these assumptions and their use for constructing a normative theory of choice (see Elster 1979, Rhodes 1985, and Sen 1987), these concerns are outside the scope of the discussions in this chapter.

Individual rationality is defined as behaviour that maximizes individual utility. If individuals acted rationally, their observed choices would maximize their utility. If their observed choices maximize their utility, a model of individual choice that performs well descriptively, will also lead to maximization of utility in sufficiently similar problems and would, therefore, be able to serve as a normative theory. Hence, the use of a descriptive model of choice as a normative theory requires that, first, individuals act rationally and, second, the situation to which a model is applied normatively is sufficiently similar to situations for which the model performs well descriptively. The development of decision theories from axioms of rational choice can be viewed as an attempt to expand the scope of a normative theory, particularly, for situations in which one of these two conditions are not met. For example, if Savage's axioms of rational choice were accepted as a normative foundation, then SEU would follow and could be used as a normative theory. The problem remains that some axioms with intuitive appeal, such as von Neumann-Morgenstern's independence axiom or Savage's sure thing principle, turn out to be systematically and consciously violated (see for example MacCrimmon and Larsson 1979). This would undermine these axioms' validity as foundations for a normative theory if individual behaviour leading to these violations is nevertheless considered rational.

2.2 Some Aspects of the Reality of Environmental Decision Making

This section attempts to describe several important aspects of the reality of environmental decision making which will lead to the requirements for a good model of environmental decision making discussed in the following section. Environmental decision making involves choices about the depletion or restoration of natural capital. Three important examples of such choices are the disposal of waste products, the depletion of natural resources, and the conversion of wildlands. The disposal of waste products includes emissions into the air or water as well as waste disposal on land. Issues arising from decisions about the disposal of waste products include the threat of global climate changes through the greenhouse effect and the depletion of the ozone layer through emissions of chlorofluorocarbons (CFCs). Decisions about the depletion of natural resources involve the consumption of fossil fuels and minerals, reductions in the stocks of forestry and fisheries, as well as the depletion of top soil resources through unsustainable agricultural practices and resulting erosion. Decisions about the conversion of wildland involve possible climate changes, the destruction of the habitat of species and subsequent loss of biodiversity, such as it is occurring at a rapid rate in many forests areas all over the world.

There are two main classes of environmental problems that decision makers are facing. One class of environmental problems involves a decision on whether to allow an economic activity, such as a project, that generates certain benefits to the entity undertaking the project and uncertain external costs through the depletion of natural capital. For example, the construction of a power plant or a hydroelectric dam generates (relatively) certain benefits, such as the value of the electricity produced. However, the costs of depleting natural capital (emitting carbon dioxide, or flooding a rainforest area) are highly uncertain and often occurring as externalities in the distant future. Similarly, the economic benefits from logging a forest or using CFCs are relatively certain while the costs associated with emissions or wildland conversion are highly uncertain. The other class of environmental problems requires a decision on whether to undertake a project that restores natural capital or reduces its depletion. In this class of problems, costs and benefits are a mirror image of those in the first class of problems. Here, costs are certain (i.e., the costs of pollution abatement equipment, or the costs of a reforestation project), and the benefits, which are the avoided costs of natural capital depletion, are highly uncertain. Of course, a practical situation may involve uncertainties in costs as well as benefits; however, the described generic structure appears to be typical of many problems in which the environmental costs and benefits are external, pervasive and often occurring at a distant time and are, therefore, more uncertain than internal and immediate costs or benefits.

Environmental decision making is often characterized by a high degree of ignorance about the costs of natural capital depletion or the benefits of its restoration. There are two main reasons for this ignorance about relevant states of the world. The first reason is the limitation of the cognitive capacity of humans compared to the complexity of natural systems. Even if we understood the functioning of all natural system, limited cognitive capabilities would still prevent us from imagining and considering all relevant states of the world. Beyond limited processing capacities of individuals, social information processing is deficient as well. For example, inadequate communication between scientists and decision makers would further reduce the completeness of state descriptions considered in a decision situation.

The second reason for ignorance is the combination of incomplete knowledge of natural systems with our capacity to undertake innovative activities whose outcome depends on the functioning of natural systems. Thousands of years of history of the natural sciences can be interpreted as a learning process about the functioning of natural systems. At every step, humans have obtained new information about the functioning of natural systems that was not available before. Obviously, this learning process is ongoing. So far, there is no indication that the natural sciences are approaching anything like a complete understanding of all natural systems. The continuing process of discovering means that states which are possible to consider after a discovery is made cannot be considered before the discovery. Even though we do not fully understand natural systems, we know how the environment responds to particular activities that were repeated many times in the past. Today, however, the extent and new types of natural capital depletion often introduces unprecedented changes. For these unprecedented forms of natural capital depletion, we have no historic experience from which we could form precise expectations about their outcomes. As a result, we are ignorant about possible outcomes to a large degree.

There are a wide range of environmental decision making problems for which ignorance is relevant. Examples of the past show how the impacts of environmental destruction could not have been considered because they were not yet known. It took many decades of using and emitting CFCs until the possible destructive effects on the ozone layer were discovered in the early 1970s. Regulators, faced with the emergence of CFCs, could not have considered the depletion of the ozone layer before this effect was first discussed in scientific circles. For a long time, carbon dioxide emissions were considered harmless, until scientists directed attention toward the possibility of global warming through the greenhouse effect. The introduction of a new drug or a new chemical is an innovative activity that can lead to relevance of unknown states of the world despite extensive testing, as the Thalidomide case demonstrates. There are many more examples for past decisions that were made not in consideration of these risks but in ignorance about possible states of the world. Similarly, we are ignorant about possible outcomes of unprecedented activities currently undertaken. The debate about possible health impacts of electromagnetic fields would be an example. The uncertainty is clearly not well described as risk. Possible interactions between human health and different types of electromagnetic fields are not yet known. Therefore, possible states of the world cannot be fully described.

In many of the mentioned examples, it is impossible to define all relevant states of the world. However, we know that we are ignorant. In fact, in some instances, we may not be surprised about the occurrence of a scenario that we could not have described beforehand. Often, it is possible to describe a scenario, or a class of similar states that, individually, are not well defined. For the introduction of a new drug, one possible scenario would include the discovery of birth defects resulting from the use of the drug by pregnant women. Another scenario would include unexpected side-effects or interference with other drugs. For the destruction of habitat and the reduction of biodiversity, an important scenario would include all states in which an extinct species could have been used later for the development of a new drug, even for a disease that is not yet known, or could have provided important genetic material for crop research. For atmospheric emissions, one scenario would include all states with unexpected climatic consequences. In each of these cases, it would be impossible to describe all individual states. However, for a scenario, there may even be historic data that shows, for example, the relative frequencies of pharmaceutically useful discoveries from a species.

Since many environmental problems involve innovative activities, ambiguity is of great importance. Probability assessments for innovative activities would be considered less reliable than those for activities for which there is considerable experience, or even statistical data. In the latter case, experts would tend to agree on a probability assessment for a particular event's occurrence. In the former case, conflicting probability assessments of experts would be likely. Consider real-life situations in which all possible outcomes of an act can be well described but no reliable, or only conflicting, information regarding their probability is available. The consequences of a large scale accident, such as an oil spill, a chemical leak, or an accident in a nuclear reactor, may be well understood (the states are well defined) but due to limited experience it is not possible to assign reliable probabilities to the possible states of the world.

Another important aspect of many environmental decision problems is that they are very different from decision situations in which the behaviour of individuals can be observed. An obvious difference from typical individual decision making is the scale of some environmental problems that can involve decisions about future living conditions on the entire planet. Also, many environmental decisions have a very long time-horizon due to the inertia of many natural systems. For example, CFCs are estimated to remain in the atmosphere for an average of 65 to 120 years after their emission (see Deutscher Bundestag 1989, p.158). It is said that deforestation undertaken by the Romans in the Mediterranean countries has significant negative effects on the climate in North-Africa, even today. Due to their short life-span, individuals would not consider such long-term aspects of their decision making. Similarly, most of the uncertain costs in environmental problems arise as externalities that are excluded from consideration in individual choice. Finally, many environmental problems are different from typical individual choices, especially those that have been studied in detail, in that they are highly complex and involve knowledge from a large number of different disciplines.

2.3 Requirements for a Theory of Environmental Decision Making

In the previous section, some important aspects of real-life environmental decision problems were discussed. They included a generic structure in which there is more uncertainty about the environmental costs than about the benefits of an investment, the prevalence of ignorance and ambiguity, and a significant difference between environmental decision making and typically observed individual choices. A theory for environmental decision making should be based on a model that reflects and does not abstract from those particularly important aspects of real life environmental decision problems. In this section, several requirements for a good normative theory of environmental decision making under uncertainty are suggested. The requirements for a suitable normative model of environmental decision making that will be discussed in this section can be summarized by two requirements for the modeling of beliefs and three additional requirements for the modeling of values. A suitable model of beliefs should, first, allow the representation of ambiguity and ignorance, and, second, allow the construction of beliefs from independent pieces of evidence. This includes the requirement for easy elicitation and aggregation of beliefs from experts. A suitable model of values should, first, be consistent with observed behaviour and be derived from an intuitively appealing set of axioms. Second, the model should be able to clearly separate decisions that are based on a theory with strong normative foundations from those based on more speculative aspects of the theory. Third, the choice rule implicit in the model of values should be robust to possible misspecifications of the model.

The discussion in the previous section has emphasized the importance of ambiguity and ignorance in environmental decision making. Therefore, a good decision model for environmental problems should allow the representation of beliefs with ambiguity or ignorance. Consider different reliabilities of probability assessments as an example of ambiguity. In environmental decision making, there is often incomplete knowledge of some of the relevant natural processes. On the other hand, some aspects of a problem may be very well understood. Similarly, an analysis may entail very different levels of detail and a likelihood judgement based on a detailed analysis with in-depth understanding of the problems involved should be distinguished from likelihood judgements based on sketchy understanding and "back of the envelope" type analysis. The question whether the reliability of probabilities does or should affect a decision will be discussed later. However, there is no reason to a-priori give away the information contained in knowledge of different reliabilities of probability assessments. In case of ignorance, there are states that are not well defined. Hence, a model that does not allow for the representation of ignorance, would force a decision maker to either ignore a scenarios, or make arbitrary assumptions about a scenario that would complete the description of the world. An important reason for explicit consideration of ambiguity and ignorance lies in the asymmetry of many environmental problems. As discussed above, controlled human-made systems and internal effects are, in general, better understood than uncontrolled natural systems and external effects. Therefore, there is more ambiguity and ignorance about environmental costs than internal benefits. Hence, the use of a model that suppresses ambiguity and ignorance can introduce a systematic bias in the decision analysis that depends on the evaluation of ambiguity and ignorance.

Many environmental problems have great complexity compared to the cognitive capacities of humans. For some complex issues, no single individual may posses all relevant information that is available in different domains of knowledge. Because of the complexity of the issues, a wholistical assessment of beliefs may be rather unreliable. For example, the willingness of individuals to purchase insurance against an environmental threat could be used to infer beliefs about the likelihood of that event. If individuals have to make decisions that depend on their assessment of environmental uncertainties, they are unlikely to use all available evidence in determining their beliefs; yet, the aggregation of different bodies of knowledge can generate new conclusions. In a complex situation, individual behaviour is likely to be influence by published opinions or existing decision making models. Therefore, individual betting rates (i.e. the amount of insurance acquired by individuals) would not be an independent guide to a good decision making model. Similarly, the elicitation of wholistic beliefs from experts would reduce the transparency of the decision making process and open the door for biases created, for example, by individual incentives of experts.

The difficulties in assessing wholistic beliefs suggests that a good theory for environmental decision making should focus on the construction of beliefs from individual pieces of evidence (see Shafer 1981). The construction of beliefs from evidence requires the decision analyst to elicit knowledge or evidence from experts. The representation of beliefs that is required by the decision making model would influence the way information is elicited from the expert. Information obtained from the expert, in turn, may be biased through the way it is elicited. The more the experts are forced to express beliefs in a form that is unnatural to their thinking, the more it would be expected that framing biases influence elicited beliefs. Thus, a good model for environmental decision making should accommodate the natural way of belief representation in the relevant domains of experts and allow the incorporation of vague beliefs. The latter requirement is, of course, related to the importance of representing ambiguity and ignorance.

The complexity of many environmental problems leads to the need to break down a problem into different components and assess beliefs over the uncertainty in sub-problems. Therefore, a good decision model would accommodate the aggregation of beliefs that were obtained from different bodies of evidence in order to assess the uncertainty in sub-problems. Even within a given sub-problem, the belief assessments of experts may diverge. In simple problems of risk, it is likely that experts would agree in their belief assessment. For example, little disagreement would be expected if different experts analyzed a standard lottery machine and had to express their beliefs about drawing a particular number. On the other hand, the complexity of environmental problems will lead different experts to come to different assessments of belief based on the same body of evidence. Therefore, a good decision model would also allow the aggregation of different beliefs based on the same body of evidence. This aggregation of divergent beliefs is particularly important since many environmental problems involve social and not individual choice due to the prominent role of externalities.

The second part of a decision model is the value function, or choice rule, that scales acts based on the assessment of the consequences of different states and acts and the beliefs over the states and scenarios. In contrast to beliefs, which have some impersonal interpretation (a person holding a particular belief would think that another person should hold the same belief based on the same body of knowledge), values are an expression of attitudes and preferences that are personal (a person would not think that another person must have the same attitude toward risk or uncertainty, even if that person was holding the same beliefs). Since the objective of environmental decision making is to increase utility of individuals, and choices of rational individuals would reveal the preferences from which utility can be derived, a choice rule should be consistent with observed behaviour toward risk and uncertainty. In order to be able to translate attitudes toward risk and uncertainty that were observed in one situation to a different situation, a choice rule should follow from intuitively appealing axioms that are consistent with observed behaviour.

In the previous section, the conditions were discussed under which a descriptive theory of choice can serve as a good prescriptive theory. Three reasons will be given here why the normative foundation for environmental decisions making is rather weak. First, one would be comfortable with applying a decision model that performs descriptively well in a particular domain of problems to a normative decision situation which is sufficiently similar. Due to the scale, the long-term implications, and the externalities, most environmental decision situations, however, are not even remotely similar to observable decision making by individuals. Since there are no observable choices, preferences of individuals over such problems are not revealed. There is no necessity for a model that describes preferences well in one domain to also describe them well in a very different domain. Second, applying a normative theory to a domain in which little empirical observations of behaviour are available may be acceptable if the theory is based on intuitively appealing axioms that are consistent with behaviour in other domains. However, as discussed in a later section, specific axioms of choice underlying SEU, as the most widely accepted decision making theory, are systematically violated in situations of ambiguity. Therefore, there is little basis for applying these axioms to environmental decision problems that are characterized by a high degree of ambiguity. Third, as discussed before, the complexity of environmental problems is large compared to human cognitive capacity. Therefore, rational individual behaviour is less likely than in simpler problems. Therefore, even if individual behaviour could be observed in environmental problems, it would not give a strong foundation for normative decision making.

The weak foundation for normative decision making, particularly in the presence of ambiguity and ignorance, makes the explicit and transparent evaluation of ambiguity and ignorance desirable. Despite many drawbacks, the most widely accepted theory for decision making under risk is expected utility theory. While many other approaches have been suggested, there exists no such widely accepted theory of decision making under ambiguity and ignorance. The difficulties with inferring preferences outside the domain of typical individual choices makes it unlikely that a generally acceptable normative model for environmental decision making under uncertainty is easily developed. Therefore, a good environmental decision theory should separate the treatment of risk from the treatment of ambiguity and ignorance. This would make it possible to distinguish conclusions that can be derived on the basis of expected utility, independent of the normative treatment of ambiguity and surprise, from those conclusions that rely on additional assumptions about the treatment of ambiguity and surprise. This would allow the isolation of conclusions from an extension of expected utility theory from potentially more controversial conclusions. Because of its general appeal, expected utility should be the special case of a more general theory for decision making under uncertainty.

The final requirement for a good theory of environmental decision making is based on the recognition that the specification of uncertainty under ambiguity and ignorance is more likely to be faulty than under risk. The discussion so far has shown that designing a good model for environmental decision problems is no trivial task. The misspecification of a model can lead to significant, possibly irreversible consequences, in environmental decision making. This suggests that the choice rule should be robust to specification errors. This requirement of robustness is not to be confused with risk aversion. In many situations, a decision maker will consciously take on some risk. Even if this risk taking leads to a negative outcome, the decision maker would still consider the original decision as correct since it took the risk explicitly into account. On the other hand, a negative outcome that was not considered by the decision maker because of a misspecification of the model would lead to regret. The decision maker would consider the original decision incorrect. The choice rule in a good decision model should, therefore, avoid regret about misspecification through robustness.

3 Approaches to Decision Making under Uncertainty

This section reviews several models for decision making under uncertainty and their suitability for environmental decision problems. After a brief description of the theories, some discussion of their aptness according to the criteria developed in section 2.3 is provided. This review is incomplete and focusses on those theories that are either widely accepted or appear to have particular potential for the analysis of environmental problems. First, subjective expected utility theory is discussed and criticised as the most widely used and accepted theory of decision making under uncertainty. Second, theories of decision making under ambiguity are analyzed. These models can be separated into those modifying the utility from ambiguous states, those based on a set of probability distributions on the states, and those based on upper and lower probabilities or belief assessments through some non-additive measures. Third, some theories of decision making under ignorance are discussed. This review excludes a large number of models that were developed to address the weaknesses of SEU to describe individual behaviour under standard risk, as for example shown in the Allais paradox. Many interesting and important theories fall into this category (i.e., prospect theory by Kahneman and Tversky 1979, or anticipated utility theory by Quiggin 1982). However, they are excluded from this review in order to focus the analysis on the deficiencies of SEU with respect to the treatment of uncertainty that is not risk.

3.1 Subjective Expected Utility Theory

The most commonly used model for decision making under risk is subjective expected utility theory (SEU). SEU assumes a measure, π, over states, ω, that is a (additive) probability distribution and a utility function of the form:

$$U_a = \sum_{i=1}^{N} \pi_i \, u(a(\omega_i)) \qquad (1)$$

In order to strengthen the theoretical foundation of this model, axioms of choice have been developed from which the representation of preferences in this particular functional form can be derived. Two of these axiomatizations were developed by von Neumann and Morgenstern (for objective probabilities) and Savage (for subjective probabilities). SEU is applicable to situations of risk only and, thus, requires the highest degree of specification of uncertainty. SEU is the model underlying most of the literature on environmental evaluation under uncertainty including evaluation techniques in cost-benefit analysis. In this section, I will argue that the inability of SEU to represent ambiguity and ignorance is a significant limitation for many environmental decision situations and is likely to bias the evaluation.

SEU assumes that all states of the world are well defined and that a unique probability distribution over these states exists. Walley (1991, p.3) calls this the "Bayesian dogma of precision". He discusses this deficiency of SEU in depth and provides references for proponents and critics of SEU. In SEU, neither ambiguity nor ignorance can be represented. All uncertainty has to be expressed in the form of risk. Two examples shall illustrate the problem of ignoring ambiguity and ignorance. First, consider two different tennis matches (for this example see Gärdenfors and Sahlin 1982). The decision maker has detailed knowledge of the skills, experiences and strategies of the players in match A and, after careful deliberation, assigns probabilities of one half to each player winning the match. On the other hand, the decision maker has never even heard the names of the players of match B and no information about them is available. In this situation, the decision maker is assumed to also assign probability one half to each player winning the match. SEU would be incapable of distinguishing these two situations with the same utility outcomes and the same probability assessment but sharply different levels of reliability of these probabilities. This means, SEU would not allow different treatment of these two matches, i.e. different betting rates.

Second, consider a situation with two states of the world, in which no information is available about the probability of those states. For example, a ball is to be drawn from an urn which contains green and red balls in an unknown number and proportion. The decision maker is asked to assess the probability of drawing a red ball. For an analysis based on SEU, a "Bayesian non-informative prior distribution" of the balls in the urn would have to be assumed. Based on the principle of insufficient reason, one sensible prior probability distribution might be one half for each of the two states. However, Arrow and Hurwicz (1972, p.2) remark:

> A state of nature is a complete description of the world. But how we describe the world is a matter of language, not of fact. Any description can be made finer by introducing more elements to be described; hence, any state of nature can be expressed as a union of more elementary states of nature.

The state green could be divided by more detailed description into the states dark green and light green. Would this consideration change the prior probability assessment for green and red to two-thirds and one-third, respectively? Then, what happens if the state red was divided into more states by more detailed description? What about dividing the state dark green even further? Clearly a non-informative prior must be based on some well defined set of elementary state of nature. Since the partition of states is a matter of description and not of fact, using a non-informative prior makes a decision arbitrarily dependent on the description of states.

These concerns apply not only to the assumed uniform distribution over two states but to all non-informative prior distributions. In the urn example, one could seek another basis for assigning a non-informative prior distribution. One could assume a uniform prior distribution across the spectrum of colours. This would make probability assignments arbitrarily dependent on the measurement of colours. Measuring the light frequency of colours would result in a different distribution than measuring heat absorption or hue. Alternatively, probability could be distributed uniformly over the range of outcomes in terms of utility. Then, the probability assessments for drawing different colours would depend on an individual's utility function, which also does not appear appealing. The simple conclusion is that a precise probability distribution cannot express lack of precision. If it was possible to define elementary, equi-probable states of the world, there would be no need to express imprecision. However, in real-life decision making, there is no pre-defined set of elementary states, and, therefore, a specific prior distribution has to be assumed (by definition of ambiguity it cannot be obtained from information about the problem) and introduces arbitrariness in the decision making process.

SEU assumes the existence of a set of well defined states of the world. If SEU is used in a situation of ignorance, problems similar to those discussed for ambiguity arise. In the presence of ignorance, there are states that cannot be fully described and cannot be associated with a single utility outcome under every act. In order to provide the information required by SEU, some assumption would have to be made about an average utility value for a scenario under a given act. Again, SEU would force the decision maker to introduce an arbitrary assumption. (The assumption is arbitrary since, by definition of ignorance, it is not based on available information.)

The inability of SEU to represent ambiguity and ignorance would restrict the elicitation of beliefs from experts. The requirement of a precise probability distribution suppresses all available information that cannot be expressed in a single probability distribution. Also, the elicitation of ambiguous beliefs would be prone to framing biases. Beliefs that are forced into single probability distribution over a fixed list of states may be more biased by uncontrollable aspects of perception or description of these states compared to elicitation that leaves more room for expressing vague beliefs. The arbitrary assumptions that experts or decision makers have to make to obtain precision could lead to systematic biases, for example, induced by a more detailed description of particular possibilities, or simply an implicitly higher weight on well understood states. While these specific biases are hypothetical, the requirement of precision requires implicit and uncontrollable assumptions that would tend to generate some bias.

By assuming a probability distribution over a well-defined set of states, SEU assumes away the difference between choice problems with probability assessments of different reliability. A normative theory that is oblivious toward the possibility of uncertainty about probabilities could be justified if there was empirical evidence that the reliability of probability assessments does not matter. To the contrary, there is considerable empirical evidence that ambiguity does matter in individual choice (see for example MacCrimmon 1968, MacCrimmon and Larsson 1970, and the review in Camerer and Weber 1992), most of which is related to the Ellsberg paradox (Ellsberg 1961). One version of the Ellsberg Paradox is shown in Table 3.1. An urn contains 30 red balls and 60 white or yellow balls. Individuals are offered a choice between two bets whose payoffs depend on the colour of one ball that will be drawn from the urn. Most individuals prefer bet f to bet g (which implies with Savage's axioms p(R) > p(W)) and prefer bet h to bet i (which implies p(R) < p(W)), where p(R) and p(W) denote the assessed probabilities of drawing a red or white ball, respectively. Hence, individuals are unable to assign consistent probabilities to the events R and W. Here, individuals show systematic preference for unambiguous events, that is they demonstrate ambiguity aversion. A large part of the literature on decision making under ambiguity deals with solutions to the Ellsberg paradox.

Balls	30	60	
Act	Red(R)	White(W)	Yellow(Y)
f	\$1000	\$0	\$0
g	\$0	\$1000	\$0
h	\$1000	\$0	\$1000
i	\$0	\$1000	\$1000

with Savage's axioms:
f ≻ g implies p(R) > p(W);
h ≺ i implies p(R) < p(W).

Table 3.1 The Ellsberg Paradox

The contradicting probability assessments in the Ellsberg paradox follow from Savage's "sure-thing principle". A few of the approaches that were taken to weaken or replace Savage's sure thing principle are summarized in section 3.2. Defenders of SEU sometimes point out that, if individuals held beliefs that do not conform to the axioms of probability, it would be possible to construct bets that would be accepted by these individuals and would generate a sure loss (this is the so called "Dutch-book argument"). The Dutch-book argument, however, is based on the assumption that an individual would always accept either one or the other side of any bet. The argument does not hold, if an individual would not be willing to accept either side of an ambiguous bet. The latter behaviour, would appear quite reasonable and invalidates the Dutch-book argument (see Gärdenfors and Sahlin 1982).

Following from the empirical analysis of choice under ambiguity, SEU does not well describe preferences in situations of ambiguity. Since individual preferences are considered the basis for normative decision making, the Ellsberg paradox and related evidence would undermine the justification for using SEU as a normative model in situations involving ambiguity. It was suggested above that the environmental costs of many activities are highly ambiguous while the benefits are less ambiguous. If ambiguity aversion was part of individual preferences, modeling environmental choices with SEU would then systematically bias decisions against environmental conservation. The deficiencies of SEU, particularly as a normative theory, and the absence of a generally accepted alternative normative model, underline the importance of making transparent the mechanisms used for deciding among ambiguous alternatives.

3.2 Decision Making under Ambiguity

Theories of decision making under ambiguity are mainly motivated by attempts to rationalize the Ellsberg paradox and find a descriptive model that is consistent with the empirical evidence regarding individual choice under ambiguity. Camerer and Weber (1992) have recently surveyed this literature. Following Camerer and Weber, the models proposed in the literature on decision making under ambiguity can be roughly divided into three major approaches. The first approach is based on modifying the utility obtained from ambiguous versus unambiguous states. The second approach retains the assumption of state independent utility and a probability measure over the set of states. However, instead of a single probability distribution, there is a set of probability distributions, which are related through either a second-order probability distribution or some measure of reliability. The third approach is based on expressing beliefs about the likelihood of states by a measure that does not fulfil the axioms of probability, such as probability intervals or non-additive probabilities. This section reviews a few of the decision models and discusses their suitability as normative models for environmental decision making.

Before entering the discussion of ambiguity models, it is important to note that in models which are not based on a single second-order probability measure (or a single probability measure of some higher order), some familiar statistical statements become meaningless. Without a single probability measure, there is no longer an expected value of the utility resulting from beliefs. Hence, if one questions the existence of a single probability measure, one would have to question the meaning of a statement that, for example, compares the expected cost of global warming with the costs of mitigating measures. Also statements about ambiguity aversion or ignorance aversion become less meaningful. With a single second order probability measure, ambiguity aversion would be shown in preference for a bet with a precise probability π over a bet with risky probability with expected value π. This statement becomes meaningless if an expected value for π is not defined. It would be possible to speak of pessimism or optimism about ambiguity only if all decision weight is put on the lowest or highest outcome. No other decision weights would warrant a label such as ambiguity-averse or ambiguity-seeking.

Some models for decision making under ambiguity are based on a modification of utility from ambiguous events rather than modification of the probability weights on these events (see Sarin and Winkler 1992 for an example). For such a theory to be useful, some structure would have to be imposed on the modifications of utility due to ambiguity. While Sarin and Wakker impose such a structure for a simple Ellsberg-type situation, there is no obvious route for extending their approach to more complex situations of ambiguity as it would prevail in many environmental problems. Without a structure that would allow the construction of ambiguous beliefs from evidence, this approach would be of limited value for environmental decision making. Moreover, the modification of utilities for the representation of ambiguity blurs the distinction between the representation of beliefs and values. This distinction, however, appears to be useful in order to increase the transparency of the decision making process in face of the weak normative foundation for decision making under ambiguity.

The simplest ambiguity models based on modification of the representation of beliefs are those with a single second-order probability distribution. This amounts to a description of a well-defined two stage lottery. To reflect ambiguity aversion, some of these models use non-linear weights on probabilities. While such models are able to explain empirical anomalies of second-order risk aversion, their normative applicability is questionable. The same real life situation could be described by different decompositions of risk which would then result in different ranking of acts. For example, a simple lottery could also be described as a two-stage lottery: a first lottery that results in a particular position of the balls through mixing; and a second, biased, lottery, in which the winner is determined by drawing a ball given the position of balls determined in the first stage. Thus, different descriptions of the same lottery could lead to different rankings of acts. A single second-order probability distribution avoids the real problem of ambiguity. It is applicable only to situations in which uncertainty is completely specified, albeit somewhat more complex than under risk. Therefore, a model with unique higher order probabilities does not help address the fundamental question how to decide in the absence of a complete specification of risk.

An example of a decision theory based on a set of probability distributions without assuming the existence of a second order probability distribution is Gärdenfors and Sahlin (1982). In their model, every probability distribution in the set of possible distributions is associated with a level of "epistemic reliability". In a first step, probability measures with an unsatisfactory level of epistemic reliability are eliminated. In a second step, every act is evaluated with the one probability measure that leads to the lowest expected utility among all probability measures that remain after the elimination process in step one. The act with the largest minimal expected utility is chosen. This model clearly represents the distinction between implications and weight of evidence. It allows representation of incomplete knowledge by introducing several distinct probability measures. Yet, evidence would need to be represented in form of probability measures, which, following the discussion of SEU, is an unnatural way to represent incomplete knowledge. Without a clear interpretation of the satisfactory level of epistemic reliability, the elimination rule introduces a somewhat arbitrary element in the decision making process. The aggregation of different beliefs is given through a maximin rule on admitted probability measures. This does not allow a distinction between different degrees of reliability of admitted probability measures or a combination of the information contained in different measures.

There is a large number of decision theories that are based on some notion of upper and lower probabilities or probability intervals with different interpretations. The essential construct to represent beliefs in these models is the lower probability, $n(\omega)$, of a well defined state, ω, or a set of states. The simplest type of lower and upper probabilities are minimum and maximum probabilities. In a lottery example, the minimum probability for drawing a ball of a particular colour could be determined from an incomplete specification of the lottery. That is, observing that one out of three balls in an urn is red (without knowing the colour of the others) allows assigning a minimum probability of one third and a maximum probability of one to the state red. In a more complex real life situation, lower probability would be some lower level of subjective belief in the occurrence of a particular state.

Like proper probabilities (that fulfil the axioms of probability), lower probabilities are real numbers between 0 and 1. However, they do not need to be additive. Hence it is possible that $n(A)+n(B) < n(A \cup B)$ and $A \cap B = \varnothing$. In most models it is assumed that lower probabilities are monotonic. This means $n(A)+n(B) \leq n(A \cup B)$ is required. Lower probabilities can be used to express situations of ambiguity. Suppose it is only known that an urn contains red (R) and green (G) balls. Then ambiguous beliefs could be expressed by, for example, $n(\{R\}) = 0$, $n(\{G\}) = 0$ but $n(\{R,G\}) = 1$. Let 2^Ω denote the set of all subsets of the set of all states, Ω. The lower probability values of all members of 2^Ω would express all beliefs in a given situation. Ambiguity would be present if $n(A)+n(B) < n(A \cup B)$ and $A \cap B = \varnothing$, where A and B are subsets of Ω. While all information is contained in the lower probabilities of 2^Ω, one can easily define an upper probability, $p(A)$, from the lower probability of the complement of A:

$$p(A) = 1 - n(\bar{A}) \quad \forall A \subset \Omega \quad (\bar{A} = \Omega \setminus A) \tag{2}$$

Equation (2) reflects the intuition that the probability of an event cannot be greater than one minus the lower probability of its complement.

For every subset of Ω, A, there is a lower and an upper probability. Figure 3.1 shows all possible probability intervals as points on a two dimensional graph. On the diagonal line, upper and lower probabilities are equal (n(A) = p(A)). This implies that A is an unambiguous event (n(A)+n(Ω\A) = 1). The white area, n(A) < p(A), describes ambiguity with the extreme of vacuous probabilities (represented by n(A) = 0 and p(A) = 1). Beliefs in the shaded area, n(A) > p(A), would not be permitted if lower probabilities are assumed to be monotonic. Otherwise, they would represent contradictions in the beliefs. The case of contradictions is not further analyzed. However, in most of the discussed theories, contradictions could be treated analogously to ambiguity with quite intuitive results.

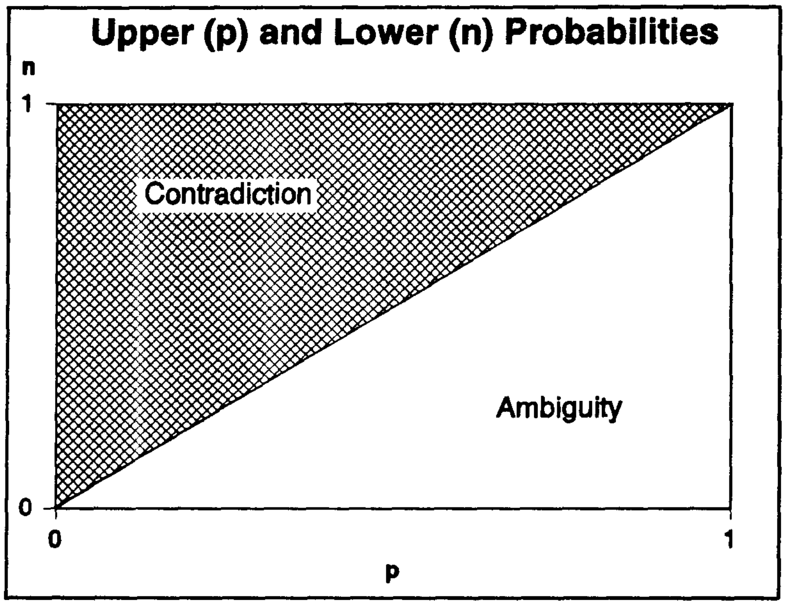

Figure 3.1 Upper and Lower Probabilities

Kyburg (1983) develops a decision theory based on a probability interval for every state. Expected utility for every act is calculated as an interval from the probability intervals over states. The lower expected utility of an act is determined by using that (additive) probability measure out of the family of probability measures falling within lower and upper probabilities that yields the lowest expected utility. The upper expected utility is calculated correspondingly by using that additive probability measure that yields the highest utility. Kyburg also defines upper probability of an event as one minus lower probability of the complement event. Kyburg's decision rule suggests that all acts, a_i, are rejected for which there is an alternative act, a_j, for which the lower expected utility exceeds the upper expected utility of a_i. This rule would order acts only partially in case of acts with overlapping expected utility intervals. Kyburg's model has been criticised since it does not provide an intuitive way for updating beliefs to reflect new evidence (see Gärdenfors and Sahlin 1988, p. 243).

Larsson (1977) shows that a non-additive measure, called P-measure, can be derived from a modification of Savage's axioms. This P-measure can be interpreted as a lower probability and fulfils the requirements listed for a lower probability. Walley (1992) discusses the importance of lower and upper probabilities at length and introduces various mathematical techniques for updating and conditioning "imprecise probabilities". Walley's upper and lower probabilities are based on a behavioural interpretation as betting rates. The lower probability of an event A, n(A), would be the supremum buying price for a lottery that pays one if event A occurs and zero otherwise. The upper probability of an event A, p(A), would be the infimum selling price for the same lottery. For an ambiguous lottery, $n(A) < p(A)$ could be interpreted as ambiguity aversion.

Lower probabilities and non-additive probabilities provide a more flexible framework for representing beliefs than an additive probability measure. Ambiguity can be expressed by explicitly assigning probability weight not to a single state but to a set of states. Ambiguity is clearly isolated as the difference between lower and upper probability of a state. This framework appears to be better suited for elicitation of beliefs from experts. Models for decision making under ambiguity do not, in general, allow the representation of ignorance. A suggestion for incorporating ignorance, however, will be presented in section 4. The models discussed so far do not provide an intuitive way for updating or combining beliefs. The Dempster-Shafer belief function theory is able to fill this gap and will be discussed in section 4. Their theory is particularly appealing for environmental decision making since it has a strong evidential rather than behavioural interpretation. The modeling of values in the approaches discussed so far does not have a strong normative foundation, partly because most of these models were designed primarily to address empirical anomalies of SEU under ambiguity.

In the areas of artificial intelligence and fuzzy set theory, some concepts are used that can be related to upper and lower probabilities. However, the primary objective of these theories is not a conceptual treatment of ambiguity as defined in this chapter. These theories are, therefore, only mentioned briefly. In possibility theory, upper and lower limits on beliefs are referred to as necessity and possibility. Possibility is understood as an ordinal and not a cardinal concept (see Dubois, 1988). Hence, possibility theory is concerned with the interpretation of statements such as "A is at least as necessary as B". Fuzzy decision theory, on the other hand, is extending the Bayesian decision making framework to fuzzy probabilities and utilities (see Zadeh, 1978, and Freeling, 1984). Acts are linked to sets of precise probabilities and utilities through membership functions. The theory amounts to an extensive sensitivity test of Bayesian decision making. Furthermore, it provides the tools to incorporate the ambiguity of real life statements such as "A is quite probable" into a systematic decision making framework. The focus of these theories is on translating statements of vague every-day language into an automatic decision support system rather than on conceptually dealing with the treatment of ambiguity. Walley (1991, p.266) remarks, "If fuzzy sets have a useful role to play, it is in modeling the ambiguity of ordinary language ... Fuzzy decision analysis ... does not appear to add anything useful to sensitivity analysis. On the contrary, [it] may obscure the decision problem, by adding second-order structure which is difficult to assess and whose meaning is unclear."

3.3 Decision Making Under Ignorance

There are few models that allow the explicit representation of ignorance. However, some very simple models of decision making under complete ignorance were proposed and are discussed here. In addition, a very different approach to decision making under ignorance developed by Shackle is briefly presented. SEU can be contrasted with models for decision making under complete ignorance, as the opposite extreme in terms of information requirements. Under complete ignorance, the only information assumed to be available is the minimum and maximum utility that can result from each act, a, denoted $u_{min}(a)$ and $u_{max}(a)$. A decision criterion can be based on a linear combination of these two utility values:

$$U(a) = \alpha u_{min}(a) + (1-\alpha) u_{max}(a), \quad 0 \le \alpha \le 1 \qquad (3)$$

This is the so-called Hurwicz criterion (Hurwicz 1951). The Hurwicz criterion has two extreme cases. With $\alpha=1$, it is the maximin criterion (the act with the highest minimum utility is chosen). With $\alpha=0$, it is the maximax criterion (the act with the highest maximum utility is chosen).

Other proposals have been made including minimizing maximum regret. Under minimax regret the alternative would be chosen under which the highest possible regret (the difference between utility obtained and utility that could have been obtained from the act with the best outcome) is smallest. However, this criterion requires information about the alignment of states (or the correlation of outcomes across acts). Another criterion, sometimes referred to as the Bayes-Laplace criterion, applies the principle of insufficient reason. If $u_{min}(a)$ and $u_{max}(a)$ is the only information available, these two utility values would be considered two elementary states which are assigned equal probability. Hence, this criterion would rank acts by comparing the arithmetic average of $u_{min}(a)$ and $u_{max}(a)$. In the context of using a non-informative prior distribution, it was discussed that $u_{min}(a)$ and $u_{max}(a)$ are not well defined elementary states of nature but merely a description of the possible range of utility outcomes. This concern applies to the latter criterion.

It is difficult to imagine a decision situation under complete ignorance. Even with innovative activities, we would have some expectation of the outcomes and some historical parallels to draw upon. For example, the release of a new chemical in the environment may clearly result in surprises. However, past experience with similar chemicals or contemplation of scenarios of possible outcomes could provide more information than only a utility range.

A decision model based on complete ignorance would discard all information other than the possible utility range. It does not appear reasonable to suggest that vague or unreliable information should not enter the decision making process at all. Therefore, decision theories for complete ignorance do not have direct policy relevance. However, these theories are useful thinking devices for contemplating an extreme hypothetical situation, and can be used as building blocks for a more complex model for situations of partial ignorance.

An interesting theory of decision making under ignorance was introduced by Shackle (1949, 1969). This theory allows a richer structure than complete ignorance while explicitly retaining the possibility of states that are not well defined. Shackle fundamentally rejects the usefulness of the probability concept to decision situations without historical precedent. He suggests a theory for decision making under ignorance that assumes the existence of a potential surprise function (ranging from zero to one) over an incomplete subset of all states of the world. He also assumes an attractiveness function (expressing what most attracts the decision maker's attention rather than referring to attraction as the decision maker's utility) over the space of utility outcomes and potential surprise. Attractiveness increases with increasing distance of the outcome of a state from the current utility level and decreases with increasing potential surprise. Those points of the potential surprise function that yield the highest attractiveness on the gain and loss side are designated as focus gain and focus loss, respectively. Acts are ranked by a decision function on focus loss and focus gain (two utility/potential surprise pairs). Perrings (1989) applies Shackle's theory to determining the size of an environmental bond that someone, who undertakes an innovative activity, should have to post in order to generate the desirable incentives for research into the outcome of such activities. Arrow and Hurwicz (1972) discuss how Shackle (1949) would interpret total ignorance as zero potential surprise of all states. Decision making under complete ignorance would then depend on the maximum and minimum payoff only regardless of the definition of elementary states of nature.

Shackle's decision theory addresses fundamentally important issues that are ignored by SEU. It accommodates the possibility of surprise and allows the expression of beliefs in the occurrence of a state through potential surprise which imposes less structure than a probability distribution. However, there would be many obstacles to using Shackle's theory for environmental decision making. There is no obvious way for constructing beliefs from evidence, integrating evidence, or combining divergent beliefs. Moreover, the model requires complex behavioural assumptions (the existence of a potential surprise function, an attractiveness function and a decision function) that would be difficult to test and appear somewhat ad-hoc. The implicit assumption that outcomes other than focus-gain and focus-loss are irrelevant is difficult to reconcile with intuition. This theory is fundamentally different from and cannot be viewed as an extension of SEU to situations of ambiguity or ignorance. At this stage, it would not be attractive to replace SEU with a theory that leaves so many questions unanswered.

4 A Model for Environmental Decision Making under Uncertainty

This section proposes a decision theory that is judged to be more suitable for normative environmental decision making than SEU, based on the requirements developed in section 2.3. The two principal elements combined in this theory are the belief function-theory by Dempster-Shafer and Choquet expected utility theory. Belief function theory provides a natural way to express beliefs that can account for ambiguity as well as ignorance. Choquet expected utility and its axiomatization provided by Sarin and Wakker (1992) provide a decision theory for non-additive probabilities that can be used on beliefs expressed by a Dempster-Shafer belief function. Combined, these two theories provide an extension of SEU to problems of ambiguity and ignorance. The components of the suggested theory for decision making under ambiguity and ignorance are not novel. The contribution of this section lies in some extensions of the Dempster-Shafer belief function theory and the demonstration how this theory can be combined with Choquet expected utility to a useful model for practical environmental decision making.

This section begins with a characterization of the representation of beliefs with the Dempster-Shafer belief function theory including Dempster's rule for combining evidence.

Some extensions of belief-function theory are suggested. These extensions would allow the representation of ignorance in a belief function. Also Dempster's rule is generalized for the integration of conditional evidence and the aggregation of different beliefs based on assessment of the same evidence. Then, the decision theory based on Choquet expected utility is presented. A lottery example illustrates the use of the suggested theory and applies it to the value of additional information about the lottery. The implications of relaxing assumptions about individual choice under ambiguity are analyzed. This latter modification leads to a model of choice under ambiguity that may not be able to order all acts completely but avoids a normative assumption about decision making under ignorance and ambiguity. Rather, the ultimate treatment of ambiguity is isolated in a behavioural parameter on which a real-life decision may, or in some instances may not, depend. Finally, the implications of the suggested theory for environmental decision making are discussed.

4.1 Representation of Beliefs

Dempster (1967) and Shafer (1976) have developed a mathematical theory of evidence that is based on belief functions. A belief function can be interpreted as a lower probability. With an additive probability measure, a total probability mass of one is divided among individual states. With a belief function, the total probability mass of one is divided among individual states but also sets of states (including possibly the set of all states). The Dempster-Shafer theory combines lower probabilities with intuitively appealing rules for the combination of independent evidence and the incorporation of statistical inference. Their theory emphasizes the construction of beliefs from evidence rather than the behavioural interpretation of beliefs as betting rates. The following is a very brief summary of those elements of Shafer's (1976) theory of evidence that are used for the proposed theory for environmental decision making.

Beliefs over the occurrence of states are expressed by a belief function, Bel. Let Ω denote the set of all states of the world and 2^{Ω} denote the set of all subsets of Ω. The same beliefs represented in a belief function can also be expressed in basic probability assignments, and belief functions are easiest explained by introducing basic probability assignments, first. The basic probability assignment, m, is a function mapping the set 2^{Ω} into real numbers between zero and one with $m(\varnothing) = 0$ and $\Sigma_{A \subset \Omega} m(A) = 1$. This means, a total probability mass of one is distributed among the subsets of Ω which may be singletons, sets of several states or Ω itself. A subset of Ω, A, is called a focal element of the belief function if $m(A) > 0$. The union of all focal elements is called the core of the belief function. The belief function, Bel, is a non-additive and monotonic measure that maps the set 2^{Ω} into real numbers between zero and one with $Bel(\varnothing) = 0$, $Bel(\Omega) = 1$ and $Bel(A) = \Sigma_{B \subset A} m(B)$. The upper probability, $P^*(A)$, is defined by $P^*(A) = 1\text{-}Bel(\bar{A})$. Bel(A) can be interpreted as the minimum and $P^*(A)$ as the maximum probability mass that can be assigned to all members of A.

A belief function generalizes subjective probabilities and allows the representation of ambiguity and probabilities with different reliabilities. Consider a situation with only two states of the world, A and B. In a situation of risk, all of the belief function's focal elements are singletons, that is $m(A) = \pi$ and $m(B) = 1\text{-}\pi$. In a situation of risk, the belief function is an additive probability measure (or a "Bayesian belief function"). A situation of ambiguity can be represented by including non-singletons in the core of a belief function. For example, $m(A) = \pi$ and $m(A,B) = 1\text{-}\pi$ would represent ambiguous beliefs. Different reliability of probabilities can be represented by making different basic probability assignments to individual states and their union. Recall the discussed example of a tennis match. Beliefs over the outcome of a match, where equal chances are assessed based on very detailed information, may be Bayesian: $m(A) = 0.5$ and $m(B) = 0.5$. For another match where equal chances are assessed on very sketchy information, beliefs might be represented by $m(A) = 0.2$, $m(B) = 0.2$ and $m(A,B) = 0.6$. Finally, if equal chances are assessed purely on the principle of insufficient reason, beliefs would be represented by $m(A,B) = 1$.

Shafer discusses several tools for the construction of belief functions from evidence. Only some of these tools are presented here. Many important details of the Dempster-Shafer belief function theory are not reported here and can be found in Shafer (1976). A basic idea of belief function theory is that evidence in real life situations is often too complex to be assessed wholistically. Therefore, Shafer suggests breaking down the evidence into simple, intuitively independent pieces, representing these pieces by a belief function, and combining the belief functions in a systematic way. Two belief functions, Bel_1 and Bel_2, can be combined using Dempster's (1967) rule. If the intersection of the cores of two belief functions, Bel_1 and Bel_2, is non-empty, that is if:

$$\sum_{\substack{i,j \\ A_i \cap B_j = \emptyset}} m_1(A_i)m_2(B_j) < 1 \tag{4}$$

the combined belief function, Bel, is expressed by the following basic probability assignments, m(A):

$$m(A) = \frac{\sum_{\substack{i,j \\ A_i \cap B_j = A}} m_1(A_i)m_2(B_j)}{1 - \sum_{\substack{i,j \\ A_i \cap B_j = \emptyset}} m_1(A_i)m_2(B_j)} \quad \forall A \subset \Omega, \; A \neq \emptyset \tag{5}$$

If the intersection of the cores of Bel_1 and Bel_2 is empty (the extreme case of irreconcilable evidence), the combined belief function will be vacuous, $m(\Omega)=1$. The belief function determined by (5) is called the orthogonal sum of Bel_1 and Bel_2, denoted $Bel = Bel_1 \oplus Bel_2$. More than two belief functions can be combined using Dempster's rule pairwise, i.e. $(Bel_1 \oplus Bel_2) \oplus Bel_3$. The orthogonal sum is transitive. Dempster's rule leads to a more focussed belief function (higher basic probability assignments on subsets with a smaller number of states) if evidence is conforming. It leads to a less focussed belief function if evidence is contradictory.

Shafer also provides a rule for the representation of beliefs from statistical inference. Suppose the set of states, Θ, consist of the possible values of a statistical parameter, θ. Shafer suggests the following equation for calculating beliefs over the parameter θ:

$$Bel_x(A) = 1-P_x^*(\bar{A}) = 1-\frac{\max_{\theta\in\bar{A}} q_\theta(x)}{\max_{\theta\in\Theta} q_\theta(x)} \quad \forall A\subset\Theta \tag{6}$$

where $q_\theta(x)$ is the likelihood of the observation, x, if the true value of the parameter was θ. This rule is a generalization Bayes' rule for updating a Bayesian belief functions. Several independent observations, x_i, can be combined using Dempster's rule.

The rule (6) shows that the theory of belief functions can provide stronger conclusions than a theory based on minimum and maximum probabilities. Consider the example of an urn with two balls of unknown colour. If one red ball was drawn from an urn, a minimum probability of one half could be assigned to the event red. However, this procedure would not exploit the full information contained in the observation. Drawing one red ball allows stronger statistical inference since it was more likely that a red ball was drawn from a population of two red balls (R,R) than from a population of one red and one other ball (R,O). This information is used with equation (6) by refining the set of states from a description of outcomes (red or other) to a description of both balls in the urn. The parameter θ ($\theta \in \Theta$, $\Theta = \{0,1/2,1\}$) would represent the share of red coloured balls in the urn. With (6), the observation of a red ball would lead to a belief function m((R,R)) = 1/2, m((R,O);(R,R)) = 1/2. This belief function would then be combined with the (Bayesian) belief function, allocating probabilities for drawing red given the composition of the urn. The result is m((R,R)) = 1/2, m((<u>R</u>,O);(R,R)) = 1/4, m((R,<u>O</u>);(R,R)) = 1/4 (the colour which is actually drawn is underlined). This leads to a basic probability assignment for drawing a red ball of 3/4 and for drawing a red or another ball of 1/4. Since beliefs do not coincide with minimum probabilities, it is possible that the true probability turns out to be outside the interval of belief and upper probability. In the above example, the belief in drawing a red ball is 3/4, and the upper probability is one. However, it may turn out that the urn contains only 1 red ball (the true probability is 1/2).

Three extensions of the Dempster-Shafer belief function theory are proposed here for the incorporation of conditional evidence, the aggregation of conflicting interpretations of the same evidence, and the representation of ignorance. Dempster's rule combines independent evidence symmetrically. However, evidence combined by Dempster's rule needs to be based on belief functions on compatible sets of states. In particular, it is required that the sets of states of two belief functions have a common partition. However, Dempster's rule is easily extended to the case where one belief function is combined with another on a subset of the set of states of the first belief function. This is the important case of integrating conditional evidence. Note that such conditional beliefs were already used in the urn example above (the belief that if the urn contains one red and one other ball, the probability of drawing a red ball is one half). The set of states of the latter belief function is a subset of the set of states of the former belief function. Suppose Bel_1 is a belief function over the set of states Ω, and Bel_2 is a belief function over the set of states Ψ, with $\Psi \subset \Omega$. Then:

$$m(A) = \begin{cases} \dfrac{m_1(A)}{1 - \sum\limits_{\substack{i,j \\ (A_k \cap B_l) \cup (A_k \setminus \Psi) = \emptyset}} m_1(A_i)\, m_2(B_j)} & \text{if } A \cap \Psi = \emptyset \\[4em] \dfrac{\sum\limits_{\substack{k,l \\ (A_k \cap B_l) \cup (A_k \setminus \Psi) = A}} m_1(A_k)\, m_2(B_l)}{1 - \sum\limits_{\substack{i,j \\ (A_k \cap B_l) \cup (A_k \setminus \Psi) = \emptyset}} m_1(A_i)\, m_2(B_j)} & \text{if } A \cap \Psi \neq \emptyset \end{cases} \qquad (7)$$

$$\forall A \subset \Omega, \quad A \neq \emptyset$$

This equation updates those beliefs in Bel_1 that are held over sets of states that include states over which beliefs are held in Bel_2 (states that are members of Ψ) in analogy to (5). Beliefs held over states that are not members of Ψ are only normalized to account for contradictions in Ψ. (7) is a generalization of (5) and collapses to (5) if $\Psi = \Omega$.

Dempster's rule is designed to combine independent evidence. It cannot be used to combine beliefs resulting from different interpretations of the same evidence. Under ambiguity and ignorance, it is perfectly reasonable that two experts with access to the same body of evidence would hold different beliefs. It would be inappropriate to combine these two beliefs by Dempster's rule. To see this consider a situation in which two experts hold the same beliefs based on the same evidence. The combination of these two belief functions does not add information to either one of them. However, use of Dempster's rule would lead to an inappropriately focussed belief function. Belief function theory, however, would offer a very convenient way of combining different beliefs resulting from the same evidence. Let "Bel_1 is included by Bel_2", denoted by $Bel_1 \subset Bel_2$, be defined as:

$$Bel_1(A) \geq Bel_2(A) \qquad \forall\, A \subset \Omega \tag{8}$$

Note that this definition also implies:

$$Bel_1(\bar{A}) \geq Bel_2(\bar{A}) \quad \rightarrow \quad P_1^*(A) \leq P_2^*(A) \tag{9}$$

Hence, if Bel_1 is included by Bel_2, the interval of beliefs and upper probabilities, Bel_1 and P^*_1, is included in the interval Bel_2 and P^*_2:

$$Bel_1 \subset Bel_2 \quad \leftrightarrow \quad Bel_2(A) \leq Bel_1(A) \leq P_1^*(A) \leq P_2^*(A) \qquad \forall\, A \in \Omega \tag{10}$$

Hence Bel_1 is more focussed and less ambiguous than Bel_2. If different experts interpret evidence differently, resulting in different belief functions, Bel_i, this is an additional source of ambiguity that can be represented in a combined belief function, Bel, which would be the most focussed belief function that still includes all beliefs, Bel_i, or:

$$Bel(A) = \min_i \left[\sum_{B \subset A} m_i(B) \right] \qquad \forall\, A \in \Omega \tag{11}$$

Finally, ignorance is not explicitly considered in the Dempster-Shafer theory. However, it can be represented in a belief function as well. Ignorance was defined as a situation in which there are some states $\omega^* \in \Omega^* \backslash \Omega$ which are not fully described. These states were called scenarios. The maximum and minimum utilities that could be obtained in scenario ω^* under act a were denoted $u_{max}(a(\omega^*))$ and $u_{min}(a(\omega^*))$. Hence, to incorporate ignorance, beliefs would be associated with the range of utility values possible under a scenario. This can be achieved through representing a scenario by two "pseudo-states" that generate maximum and minimum utility under each act. The belief in the occurrence of a scenario can be represented by belief in the occurrence of these two pseudo-states. The pseudo-states associated with a scenario, ω^*, are denoted by $\omega^* = \{\omega^{*\$}, \omega^*_{\$}\}$ with $u(a(\omega^{*\$})) = u_{max}(a(\omega^*))$ and $u(a(\omega^*_{\$})) = u_{min}(a(\omega^*))$ for all a. Now, the two pseudo-states that constitute a scenario can be treated like any other states. However, basic probability assignments can only be made to the couple of associated pseudo-states. Hence, $m(\{\omega^{*\$}\}) = 0$ and $m(\{\omega^*_{\$}\}) = 0$ would be required. Basic probability assignments can be made to a couple of associated pseudo-states (representing an individual scenario) as well as to sets of scenarios and other states. This allows a unified treatment of ignorance and ambiguity and uses all the information that is available about scenarios. Because of this unified treatment of ambiguity and ignorance, I will generally only use the term ambiguity in the remainder of this section.

4.2 Decision Theory

Dempster and Shafer do not explicitly consider their belief function theory as a decision theory. However, belief function theory can be suitably combined with a decision rule that is an extension of SEU to non-additive probabilities. Sarin and Wakker (1992) provide an axiomatization for calculating expected utility with non-additive probabilities based on an earlier paper by Choquet (1953-54). This theory is called "Choquet expected utility" (CEU). CEU is a generalization of SEU to non-additive probabilities. Implicitly, CEU assigns the probability weight that is not assigned to a single state but a set of states to the individual state out of this set that leads to the lowest utility under an act. This ambiguity-pessimism built into CEU is derived from an axiom of cumulative dominance that replaces the sure thing principle in the Savage axioms. The axiomatization has intuitive appeal, and the results of this theory are consistent with empirical evidence, such as the Ellsberg paradox.

Since the sum of non-additive probabilities over all states can be less than one, expected utility cannot be calculated directly with non-additive probabilities (see also Larsson 1977, p.147). However, Choquet (1953-54) has introduced an approach that makes it possible to calculate the expected utility from a non-additive measure such as the belief function introduced above. To calculate CEU of an act, a, with finite states, ω, states are sorted by their utility outcome: $u(a(\omega_1)) \leq \ldots \leq u(a(\omega_N))$. Then:

$$CEU(a) = u(a(\omega_1)) + \sum_{n=2}^{N} \left(u(a(\omega_n)) - u(a(\omega_{n-1})\right) Bel_a(\Omega_{n-1}) \tag{12}$$

where $Bel_a(\Omega_{n-1})$ is defined as the belief in all states that, under act a, generate utility $u(a(\omega_{n-1}))$ or higher:

$$Bel_a(\Omega_{n-1}) = Bel\left(\{\omega \in \Omega \mid u(a(\omega)) \geq u(a(\omega_{n-1}))\}\right) = \sum_{A \subset \Omega_{n-1}} m(A) \tag{13}$$

CEU calculates an expected value from non-additive probabilities by forming the expectation based on the difference between cumulative probabilities of better-than utility sets. Since $p(\varnothing) = 0$ and $p(\Omega) = 1$, the sum of the differences of cumulative probabilities is always one even if p is non-additive, which means that an expected value can be calculated. If p is an additive probability measure (or Bel is a Bayesian belief function), CEU is equal to SEU.

An appealing feature of CEU is that several axiomatizations for CEU with non-additive probabilities are available. After previous axiomatizations of CEU by Gilboa (1987) and Schmeidler (1989), a more intuitive axiomatization has been provided recently by Sarin and Wakker (1992). In their axioms, Savage's sure thing principle (which is violated by the Ellsberg paradox) is replaced with an axiom of cumulative dominance. Cumulative dominance requires "... that if receiving consequence α or a superior consequence is considered more likely for an act f than for an act g, for every α, then the act f is preferred to the act g." (Sarin and Wakker 1992, p.1256). In addition, Sarin and Wakker require a sufficiently rich set of unambiguous acts.

The cumulative dominance axiom, and hence CEU, implies that basic probability assignments for a set of states are allocated to the member of this set that yields the lowest utility outcome for the act to be evaluated. To see this, consider the (additive) probability measure $p_a(\Omega)$ with $p_a(\omega)$ defined as the sum of the basic probability assignments over all subsets of Ω whose member that generates the lowest utility under act a is ω:

$$p_a(\omega) = \sum_{\{A \subset \Omega \mid \omega \in A \text{ and } u(a(\omega)) \leq u(a(\omega_i)) \ \forall \omega_i \in A\}} m(A) \tag{14}$$

Then:

$$\begin{aligned} CEU(a) &= u(a(\omega_1)) + \sum_{n=2}^{N} \left[\left(u(a(\omega_n)) - u(a(\omega_{n-1})\right) \sum_{i=n-1}^{N} p_a(\omega_i) \right] = \\ &= \sum_{n=1}^{N} p_a(\omega_n) u(a(\omega_n)) \end{aligned} \tag{15}$$

which is SEU with probability measure $p_a(\Omega)$. Note that, by definition of $p_a(\Omega)$, every act, a, is evaluated with a different probability measure, $p_a(\Omega)$. This shows that the information contained in a belief function cannot be reduced to the information in a single probability measure. As a result of the cumulative dominance axiom, the evaluation function assigns probability weights on non-singleton sets of states to the state that yields the lowest utility under the act to be evaluated. This "pessimistic" treatment of ambiguity is discussed in a later section in more detail.

4.3 An Illustrative Examples

The example for illustrating the proposed theory is based on drawing balls from an urn. Even though such an example cannot illustrate the complexities of a real life problem, it demonstrates the operation of the proposed theory in as simple a manner as possible. One ball is to be drawn from the urn. Utility is assumed to be 1 for drawing a green ball (G) and 2 for a red ball (R). The urn contains two balls. Each of the two balls may be either red or green. Further information about the composition of the urn and how it was obtained is not available. This set-up can be regarded as a two-stage lottery. The first stage is not well defined and determines the composition of the urn. The second stage is well specified with a ball being drawn from an urn with the composition determined in the first stage.

The combined lottery has four relevant states (describing the composition of the urn and, if the urn contains balls of different colours, the colour of the ball drawn, shown as underlined): $\Omega = \{(G,G);(\underline{G},R);(G,\underline{R});(R,R)\}$. There are two sources of beliefs about this lottery. One source of belief is the assessment that the probability of drawing a particular coloured ball equals the proportion of balls of this colour in the urn. This belief can be expressed in a conditional Bayesian belief function, Bel_1. In the example, the core of this belief function is $m_1((\underline{G},R)|(G,R)) = 0.5$ and $m_1((G,\underline{R})|(G,R)) = 0.5$. The second source of belief is knowledge that will be acquired about the composition of the balls in the urn. This belief can be expressed in a belief function Bel_2 over 2^Y where Y is the set of possible compositions of the urn; $Y = \{(G,G);(G,R);(R,R)\}$. Without any additional knowledge about the composition of the urn, Bel_2 is vacuous, and the core of Bel_2 is trivially $m_2((G,G);(G,R);(R,R)) = 1$. Combining Bel_1 and Bel_2 with the rule in (7) leads to a new belief function, Bel_3, over 2^Ω with the core $m_3((G,G);(\underline{G},R);(R,R)) = 0.5$ and $m_3((G,G);(G,\underline{R});(R,R)) = 0.5$.

Panels (a) through (d) in Figure 3.2 show how the evaluation of this lottery evolves with increasing information acquired about the colour of the balls in the urn. Panel (a) shows the evaluation of the lottery based on Bel_3. From Bel_3, the CEU for this lottery can be calculated. The line on top of the light shaded area shows the belief that the realized level of utility will be at least U*. Hence in Panel (a), the light shaded area equals CEU of Bel_3. Bel_3 represents the information that the urn contains two balls that may be red or green (see Panel (a)). No state yields utility less than one. Therefore, $Bel(U \geq U^*) = Bel_3(\Omega) = 1$ if $U^* \leq 1$. The belief that utility is greater than one equals the belief in occurrence of the set

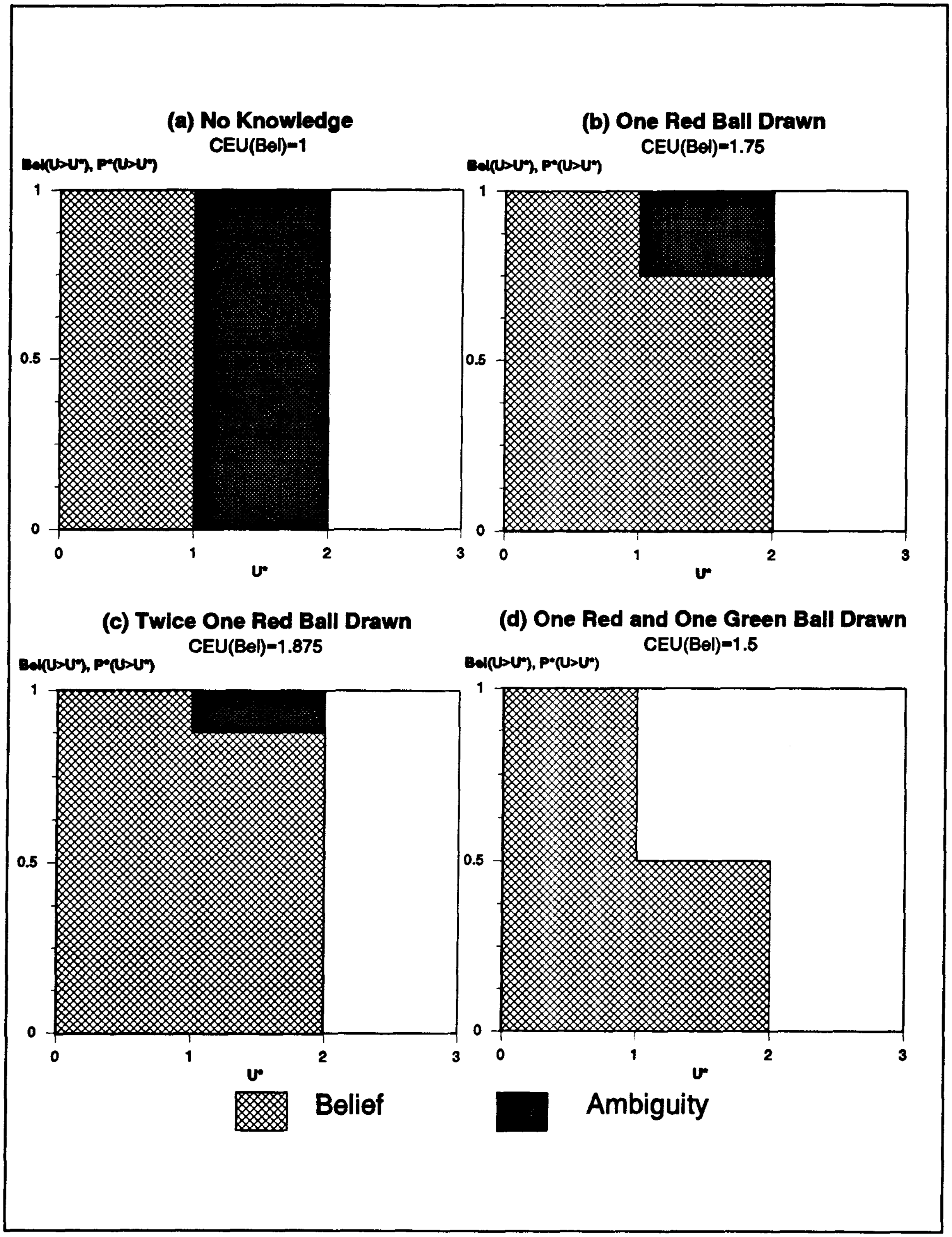

Figure 3.2 Evaluation under Ambiguity: A Lottery Example

of states that yields utility greater than one: $Bel(U \geq U^*) = Bel_3((G,\underline{R});(R,R)) = 0$ if $U^* > 1$. Hence CEU equals one. To show the degree of ambiguity, it is instructive to compare beliefs with upper probabilities. The line on top of the light and dark shaded areas together represents the upper probability that the realized level of utility will be at least U*. Upper probabilities, P*, are calculated by subtracting the belief in the complement set from one. For $U^* \leq 1$, trivially $P^*(U \geq U^*) = 1 - Bel_3(\emptyset) = 1$. With $U^* > 1$, $P^*(U \geq U^*) = 1 - Bel_3((G,G);(\underline{G},R)) = 1$. The dark shaded area shows the prevailing ambiguity.

Subset $X \in 2^Y$	$P_2^*(Y \backslash X)$	$Bel_2(X)$	$P_2^*(X)$	$m_2(X)$
{(G,G)}	1	0	0	0
{(G,R)}	1	0	1/2	0
{(R,R)}	1/2	1/2	1	1/2
{(G,G);(G,R)}	1	0	1/2	0
{(G,G);(R,R)}	1/2	1/2	1	0
{(G,R);(R,R)}	0	1	1	1/2
{(G,G);(G,R); (R,R)}	0	1	1	0

Table 3.2 Belief Function after Observing One Red Ball

In a second step it becomes known that one red ball was obtained in a random draw from the urn (see Panel (b)). From this statistical evidence a new belief function, Bel_4, over 2^Y can be calculated from (6). As discussed before, the core of Bel_4 would be $m_4((R,R)) = 0.5$ and $m_4((R,R);(G,R)) = 0.5$. The values for Bel_4 are shown in Table 3.2. Combined with

Bel_1, we obtain Bel_5 with the core $m_5((R,R)) = 0.5$, $m_5((R,R);(\underline{G},R)) = 0.25$ and $m_5((R,R);(G,\underline{R})) = 0.25$. Now $Bel(U \geq U^*) = Bel_3(\Omega) = 1$ if $U^* \leq 1$ and $Bel(U \geq U^*) = Bel_5((G,\underline{R});(R,R)) = 0.75$ if $U^* > 1$. Hence, CEU equals 1.75.

In a third step, new information is received that in a second, independent, random draw from the same urn, a red ball is drawn again (see Panel (c)). Since both observations are independent and both observations are represented by the belief function Bel_4, the combined belief function, Bel_6, can be obtained from Dempster's rule: $Bel_6 = Bel_4 \oplus Bel_4$. Combine Bel_6 with Bel_1 to obtain Bel_7. The core of Bel_7 is $m_7((R,R)) = 0.75$, $m_7((R,R);(\underline{G},R)) = 0.125$ and $m_7((R,R);(G,\underline{R})) = 0.125$. Now $Bel(U \geq U^*) = Bel_7(\Omega) = 1$ if $U^* \leq 1$ and $Bel(U \geq U^*) = Bel_7((G,\underline{R});(R,R)) = 0.875$ if $U^* > 1$. Hence, CEU equals 1.875. It can be easily verified that upper probabilities are not affected by the evidence obtained in steps (b) and (c).

In a final step, the draw of a green ball is reported. This observation leads to complete knowledge of the composition of the urn, (G,R), expressed in Bel_8 with the core $m_8((G,R)) = 1$. Hence, the resulting belief function, $Bel_9 = Bel_1 \oplus Bel_8$, is Bayesian with the core $m_9((\underline{G},R)) = 0.5$ and $m_9((G,\underline{R})) = 0.5$ with CEU = 1.5 (see Panel (d)). In this case, all ambiguity is resolved and CEU = SEU.

Table 3.3 summarizes the evolution of this lottery's evaluation. Also in this table, evaluation with CEU is compared with SEU using two different Bayesian prior distributions. The example illustrates the problems discussed above concerning selection of a Bayesian non-informative prior distribution. The question is whether two indistinguishable states, (G,R) and (R,G), should be treated as one or two elementary states of nature. If they are treated as distinct elementary states, a uniform prior distribution would assign probabilities of 0.25 to the states (G,G), (R,G), (G,R), and (R,R), respectively (shown as SEU(1)). If they are treated as one state, a uniform prior would assign probability 0.333 to the states (G,G), (G,R) and (R,R), respectively (shown as SEU(2)). The evaluation in Table 3.3 is obtained from a posterior probability distribution, $\psi(Y)$, updated from the respective prior distribution, $\phi(Y)$, with Bayes' rule:

Stage	**Belief Function**	**CEU**	**SEU(1)**	**SEU(2)**
(a) No Knowledge	$Bel_3 = Bel_1 \oplus Bel_2$: $m_3((G,G);(\underline{G},R);(R,R)) = 0.5$ and $m_3((G,G);(G,\underline{R});(R,R)) = 0.5$.	1.000	1.500	1.500
(b) One Red Ball Drawn	$Bel_5 = Bel_3 \oplus Bel_4$: $m_5((R,R)) = 0.5$, $m_5((R,R);(\underline{G},R)) = 0.25$ and $m_5((R,R);(G,\underline{R})) = 0.25$.	1.750	1.750	1.833
(c) Twice One Red Ball Drawn	$Bel_7 = Bel_5 \oplus Bel_4$: $m_7((R,R)) = 0.75$, $m_7((R,R);(\underline{G},R)) = 0.125$ and $m_7((R,R);(G,\underline{R})) = 0.125$.	1.875	1.833	1.900
(d) One Red and One Green Ball Drawn	$Bel_9 = Bel_7 \oplus Bel_8$: $m_9(\{\underline{G},R)) = 0.5$ and $m_9((G,\underline{R})) = 0.5$.	1.500	1.500	1.500

Table 3.3 Summary of Lottery Evaluation

$$\psi(\upsilon \mid x) = \frac{f(x \mid \upsilon)\phi(\upsilon)}{\sum_i f(x \mid \upsilon_i)\phi(\upsilon_i)} \qquad \textbf{(16)}$$

where x is the observation (i.e. one or two red balls drawn) and $f(x \mid \upsilon)$ is the likelihood function for drawing a ball of specified colour from an urn with a share υ of balls of this colour. Note that depending on the prior distribution used, SEU can be larger or smaller than

CEU. Of course, if the belief implicit in using one of these priors was genuinely held, this could be expressed in an additional belief function. If such a Bayesian belief function was combined with the belief function obtained from statistical inference, SEU and CEU would be identical at all stages of this lottery. The point of this example, though, is to show how the lottery can be evaluated without belief in a prior distribution.

In a practical decision making situation, learning more about a problem may be an additional alternative to accepting or rejecting a lottery. For making a choice between these three acts, it is necessary to determine the value of information obtained from learning. The value of information can be calculated for the above example. Consider a situation in which one red ball has been drawn from the urn at random (the situation in Panel (b)). Now, it is assumed that the decision maker faces three alternatives: buying the lottery at a price of 1.6 (in utility), rejecting the lottery (and receiving 0 utility), or learning more about the lottery by drawing one more ball at random and deciding afterwards whether to accept or reject the lottery. We are interested in the value of the third alternative which is the difference between the value of the lottery with and without the information obtained from learning.

Under the Bayesian approach, calculation of the value of information is straightforward, but it depends on the assumed prior distribution. Using the prior of SEU(1), without the learning option the lottery should be accepted, and its value would be 0.15 (=1.75-1.6). The value of the lottery with the learning option depends on the expectation about the outcome of the second draw from the urn and the action chosen as the result of learning. The probability of drawing a red ball would, at this stage, be assessed as 0.75. If a red ball is drawn, the lottery's value would be 0.233 (=1.833-1.6; see Table 3.3). If a green ball is drawn (probability 0.25), the lottery would be rejected since its value would be negative (1.5-1.6), and the outcome under this alternative would be zero. Hence the value of the lottery with learning option is 0.175 (=0.75·0.233). The value of information is 0.025 (=0.175-0.15). Similar calculations lead to a value of information of 0.017 for the prior distribution used in SEU(2).

The value of information can be calculated analogously for CEU. The value of the lottery without the learning option is 0.15 (=1.75-1.6). If a red ball is drawn, CEU of the lottery would be 0.275 (=1.875-1.6; from Table 3.3). If a green ball was drawn the lottery would be rejected (outcome zero). Of course, the expectations about the outcomes of learning are not expressed in probabilities but in a belief function (m(R) = 0.75, m(R,G)=0.25; see Panel (b)). CEU can be calculated by replacing the colour of the ball drawn with the utility outcome, and would be 0.20625 (=0.75·0.275). The resulting value of learning is 0.05625 (=0.20625-0.15). The results are summarized in Table 3.4. The fact that the value of learning is significantly higher for CEU than for SEU can be intuitively explained by the absence of a prior distribution in the calculation of CEU. Since CEU is based on less prior information, new information has a larger effect on the assessment of beliefs, and hence a higher value.

	(a) Value if red ball drawn	(b) Value if green ball drawn	(c) Value with learning	(d) Value without learning	(e) Value of information [(c)-(d)]
CEU	0.275	0	0.20625	0.15	0.05625
SEU(1)	0.233	0	0.175	0.15	0.025
SEU(2)	0.3	0	0.25	0.233	0.017

Table 3.4 The Value of Information

4.4 An Extension with Incomplete Ordering

As a result of the cumulative dominance axiom, CEU implies ignorance toward the possibility of superior consequences unless there is actual belief in the occurrence of superior consequences. To see this, consider the first stage of the lottery described in section 4.3 (see

Panel (a) in Figure 3.2). At this stage, beliefs are vacuous and CEU=1. Compare this lottery to a certain outcome of U=1 which would also be evaluated with CEU=1. Hence, the proposed theory implies indifference between obtaining U=1 for sure and a lottery with minimum utility 1 and the possibility of a superior consequence, i.e. U=2, if no strictly positive basic probability is assigned to consequences with utility strictly greater than 1. This demonstrates the pessimism about ambiguity built into CEU. The defense of this theory is that if the lottery was preferred to the sure outcome, this shows that there is some strictly positive belief in the occurrence of a superior consequence. For example, the mere knowledge of the existence of red balls in the universe may lead the decision maker to assign some belief to a red ball being contained in the urn. Then the lottery would be preferred to the sure consequence.

The weak foundation for a normative model of choice under ambiguity was discussed before in the context of SEU. CEU may be considered to have a somewhat stronger normative foundation than SEU since it is not as clearly inconsistent with empirical evidence shown in connection with the Ellsberg paradox. Also, CEU is consistent with a cautious "no-regret" approach to ambiguity. While the use of CEU appears to be preferable to the use of SEU, and other reviewed theories, it would, nevertheless, be an overstatement to claim that the intuitive appeal of the cumulative dominance axiom alone provides a very solid foundation for the normative use of CEU. Therefore, this section seeks to explore whether any meaningful statements about choice under ambiguity can be made without an assumption about the treatment of ambiguity, that is without accepting the cumulative dominance axiom.

Ambiguity in a given problem is reflected by the existence of many (additive) probability distributions, $\pi_i(\Omega)$, that are included by the belief function, Bel(Ω) (see the definition in (8)). If the same ranking between two acts could be obtained by using <u>SEU</u> with any $\pi_i(\Omega)$ that is included in Bel(Ω), it could be said that a ranking between these two acts is independent of the normative treatment of ambiguity. Put differently, if $\max(SEU(a,\pi_i(\Omega))) < \min(SEU(b,\pi_i(\Omega)))$ for all $\pi_i(\Omega)$ that are included by Bel(Ω), it can be concluded that act b can be chosen over act a without having to resort to any assumptions about the normative treatment of ambiguity. This approach, of course, does not guarantee a complete ordering of acts and is strongly related to Kyburg's (1983) theory, which was introduced before.

With the cumulative dominance axiom, the value function allocates the basic probability assignment of a set of states to the state with the lowest utility in this set. From (15) follows that:

$$\min_{\pi_i(\Omega) \subset Bel(\Omega)} SEU\big(a, \pi_i(\Omega)\big) = CEU(a) \tag{17}$$

where $\subset$ denotes 'included by' as defined in (8). Similarly, $\max(SEU(a,\pi_i(\Omega)))$ is equal to CEU*(a), which denotes Choquet expected utility calculated from the upper probabilities rather than beliefs. Analogous to (12), CEU* is defined as:

$$CEU^*(a) = u(a(\omega_1)) + \sum_{n=2}^{N} \big(u(a(\omega_n)) - u(a(\omega_{n-1}))\big) P_a^*(\Omega_{n-1}) \tag{18}$$

where $P_a^*(\Omega_{n-1})$ is the upper probability of all states that, under act a, generate utility $u(a(\omega_{n-1}))$ or higher:

$$P_a^*(\Omega_{n-1}) = 1 - Bel\big(\{\omega \in \Omega \mid u(a(\omega)) < u(a(\omega_{n-1}))\}\big) \tag{19}$$

where states are again assumed to be sorted by their utility outcome: $u(a(\omega_1)) \leq \ldots \leq u(a(\omega_N))$. CEU*(a) would reflect the most optimistic attitude toward ambiguity. (CEU* could also be obtained by reversing the cumulative dominance axiom. With the reversed axiom, the value function would allocate the basic probability assignment of a set of states to the state with the highest utility in this set. This assumption would lead to ignorance toward downside possibilities.)

Let V(a) be a value function for the act a that does not depend on assumptions about the treatment of ambiguity. Then, V(a) can be bounded by CEU(a) (based on an allocation of all basic probability assignments to the state with the lowest utility) and CEU*(a) (based on an allocation to the state with highest utility):

$$CEU(a) \leq V(a) \leq CEU^*(a) \tag{20}$$

If all ambiguity is resolved (the core of the belief function consists of singletons only), CEU(a) = V(a) = CEU*(a). If there is ambiguity, CEU(a) < CEU*(a). Then V(a) is bounded by an interval and does not necessarily order all states completely. However, if V(a) > V(b), or CEU(a) > CEU*(b), a can be chosen over b without the need to resort to assumptions about the treatment of ambiguity. If the intervals of two acts, V(a) and V(b), overlap, the two acts cannot be ordered unless assumptions are made about the attitude toward ambiguity, as expressed, for example, in the cumulative dominance axiom. In the example of Figure 3.2, CEU is represented by the light shaded areas in Panels (a) to (d). CEU* would be represented by the light and dark shaded area together (CEU*(a) = 2, CEU*(b) = 2, CEU*(c) = 2, CEU*(d) = 1.5). The advantage of this extension is that it can isolate decisions that can be made without assumptions about attitude toward ambiguity, based on the interval V(a) alone, from those decisions that require additional assumptions, i.e. the cumulative dominance axiom. This approach appears to be useful to make transparent the treatment of ambiguity in a given decision problem.

Analogous to the Hurwicz criterion for complete ignorance, one could propose a decision theory in which V takes the form of a linear combination of CEU and CEU* that would allow complete ordering of acts:

$$V(a) = (1-\alpha)CEU(a) + \alpha CEU^*(a) \quad with \;\; \alpha \in [0,1] \tag{21}$$

where α is behavioural parameter of optimism about ambiguity. While this may be a route for future research, currently there is neither an axiomatic foundation for such a representation nor empirical evidence that would support choice of a specific α. Also, it should be emphasized again that in a model of decision making under ambiguity, probability weights are assigned to sets of states. Since there is no assumption about a well defined set of elementary states, there is no basis for assigning probability weights to any of the states in this set, except for the states with minimum and maximum utility within the set. Since expected utility within a set of states is not defined, ambiguity aversion and ambiguity seeking are not defined. Hence, a specific α cannot be used to express a specific degree of ambiguity aversion.

4.5 Implications for Environmental Decision Making

In the previous sections, I have proposed a combination of the Dempster-Shafer belief function theory and Choquet expected utility based on Sarin and Wakker's axiomatization as a normative theory for environmental decision making. This theory was selected based on the requirements for a suitable decision model that were discussed in section 2.2. Let us examine the proposed theory in light of these criteria. Ambiguity can be expressed by basic probability assignments to sets of more than one state. Similarly, the degree of confidence in a probability assessment can be expressed by combining a belief function representing the evidence with a belief function on the reliability of the evidence obtained. Ignorance can be incorporated by basic probability assignments to pseudo-states for the maximum and minimum utility from a scenario. The Dempster-Shafer belief function theory is explicitly designed to represent beliefs obtained from evidence rather than inferred from behaviour. As a generalization of an additive probability measure, a belief function gives experts a broader choice for expressing their beliefs in the presence of ambiguity. Dempster's rule provides for the elegant aggregation of beliefs obtained from independent evidence. I have shown how beliefs of different experts based on the same evidence can be pooled. The proposed theory is a generalization of SEU for situations of ambiguity and ignorance. In contrast to SEU, the theory is consistent with empirical evidence of individual choice under ambiguity. Sarin and Wakker provide intuitively appealing axioms for CEU as the choice rule for non-additive probabilities. Even if the normative conclusions obtained from the cumulative dominance axiom are not accepted, partial ordering of acts is still possible based on SEU and all probability distributions that are included by the belief function. The extension with partial ordering shows which decisions can be made without assumptions about attitudes toward ambiguity. The use of CEU leads to more robustness toward specification errors since CEU tends to favour postponing an ambiguous act in favour of additional learning about the problem.

For decision making under risk it is well recognized that the contexts of an individual decision needs to be considered. This means that possible gains are treated as additions to and losses as subtractions from current wealth. As a result, a risk averse individual is averse to risks in losses as well as gains. Similarly with risk aversion, the certainty equivalent of a cost is higher than its expected value, and the certainty equivalent of a benefit is lower than its expected value. The context may include risks that depend not on the current decision alone. Then, it is necessary to analyze the correlation between the risks resulting from a specific choice and other risks. Wilson (1982) shows how to consider risks in projects with returns that are correlated with social risks. Even though an act, considered in isolation, is risky, it may reduce social risk if it is negatively correlated. Then, with risk aversion, this risky act would be evaluated more favourably than a certain act.

Now, the same considerations apply to the evaluation of an ambiguous act. CEU implies pessimism about ambiguity, Hence, ambiguous costs would weigh higher, and ambiguous benefits would weigh lower than costs or benefits without ambiguity. A project with ambiguity that is correlated with social ambiguity would be relatively more attractive if the correlation was negative and less attractive if the correlation was positive. Note that even in the presence of ambiguity, it may be possible to make a statement about correlation with already existing ambiguity if an act is chosen that offsets or increases the physical condition that gives rise to the ambiguity. We can now recall the introductory discussion in which it was argued that the unknown consequences of natural capital depletion are an important source of ignorance and ambiguity in environmental decision problems. Consider a decision on whether to reduce the depletion of natural capital, i.e., to limit logging or to undertake a reforestation project. Such an activity that, viewed in isolation, yields ambiguous gains and might, therefore, be evaluated at a low CEU, would in fact reduce or insure against an ambiguity that is already present. For example, a reforestation project may be associated with ambiguous gains since there is ambiguity and ignorance about the long-term benefits from a forest. However, a reforestation project that is undertaken to offset deforestation, in fact reduces the ambiguity about future well-being since it helps maintain the biological status quo that is associated with less ambiguity than a situation of large-scale deforestation. Hence, taking into account this context, the gains from this reforestation project would be evaluated more highly under CEU.

From this discussion follows that, in typical environmental decision problems, there are two stylized acts to choose from. The first act implies the depletion of natural capital (i.e., the decision not to restrict emissions, not to undertake a reforestation project, or to go ahead with a resource depletion project) and will be called the unsustainable act, a_u. The second act implies the conservation of natural capital or compensation for natural capital depletion (i.e., the decision to restrict emissions, undertake a reforestation project, or not to undertake a resource depletion project without compensation) and will be called the sustainable act, a_s. In this stylized form, the decision problem involves a choice between the unsustainable act, which is ambiguous, and the sustainable act, which is unambiguous. An unambiguous act is defined as an act whose outcome does not depend on ambiguous states. Therefore, CEU and SEU of an unambiguous act would be equal.

Now, it can be shown that the use of SEU in a situation of ambiguity leads to a systematic bias in favour of the unsustainable act. Since the sustainable act is assumed to be unambiguous, $CEU(a_s) = SEU(a_s)$. It is reasonable to assume that the probability distribution, $\pi(\Omega)$, used for calculating SEU of the unsustainable act, would be included by the Belief function that would be used for calculating CEU. It was shown before that:

$$\min_{\pi_i(\Omega) \subset Bel(\Omega)} SEU(a, \pi_i(\Omega)) = CEU(a) \tag{22}$$

Therefore, $CEU(a_u) \leq SEU(a_u)$ if $\pi \subset Bel$. Unless $CEU(a_u) = SEU(a_u)$, SEU over-values the unsustainable act compared to CEU. Since CEU and SEU value the sustainable act equally, SEU leads to a systematic bias in favour of the unsustainable act, as compared to CEU, which was judged to have a stronger normative basis for decision making under ambiguity than SEU. CEU would choose the sustainable act whenever SEU does. However, there are also situations in which CEU would choose the sustainable act while SEU would choose the unsustainable act. CEU puts the "burden of proof", or the burden to reduce the ambiguity, on the unsustainable act, which leads to the ambiguity. In the absence of any knowledge about the unsustainable act (a vacuous belief function over the possible utility range), use of CEU would lead to choosing the sustainable act as a default.

It was discussed before that even though normative use of CEU is preferable to SEU, the foundation for normative use of CEU is not fully satisfactory. Nevertheless, I suggest that a decision rule based in CEU be adopted based on the following reasoning. If the normative basis for CEU, obtained from the cumulative dominance axiom, is not accepted, and the value function intervals for a_s and a_u overlap (see (20)), no normative statement could be made about choice under ambiguity. If a decision between a_s and a_u needs to be made nevertheless, the critical question becomes which of the two acts needs a normative justification to be chosen. In this case, I would argue that using CEU (instead of CEU*) and favouring the sustainable act reflects an intuitively appealing no-regret or robustness strategy toward ambiguity. Recall the example in section 4.3, which demonstrated how the value of information would be considerably higher under CEU compared to the use of a Bayesian prior distribution. This suggests that under CEU, the learning option, which implies delaying the ambiguous activity, would often be the optimal choice. Hence, the unsustainable act would require a normative justification. Then, CEU should be used for choosing between a_u and a_s even if its normative basis is not fully accepted. It should be added that there is, clearly, no symmetry between CEU and CEU*. Neither empirical evidence nor intuition would suggest the optimistic attitude about ambiguity implied in CEU*. CEU* was introduced only to define a sensible (but extreme) upper bound on the value function.

The proper definition of alternative acts is of crucial importance in any decision making problem. Above, the sustainable act was compared with the unsustainable act. This reflects a typical situation of deciding about whether to implement a project or go ahead with an activity. In many real life situations there is a third option: learning more about the uncertainty before deciding whether or not to undertake the activity in question (see also Pindyck 1991 for a discussion of the option value of delaying an irreversible investment decision). It was suggested that this third alternative would be chosen more often under

CEU. Of course, information has value only if actions are delayed until the information is obtained. It is worthless to study ambiguity while the act is undertaken that generates the ambiguity (i.e. while the forest is cut, or the emissions are made). This point has policy relevance, for example, in the context of the discussion about emissions of greenhouse gases and CFCs. Often, the argument is made that more information is required before emission reduction should be imposed. However, if current emissions are the cause of ambiguous damages, the relevant alternative acts are continued emissions, emission reduction, or emission reduction with learning. The suggested alternative of continuing emissions and learning simultaneously is misleading since information will have no value if it does not lead to additional choices (i.e. if the damage has been caused by the time information will be received). In the real-life policy debate, it often appears that the burden of proof lies on those who want to change a current course of action. However, delaying a decision for the purpose of further learning should not mean continuing the current activity but delaying the activity that is cause of the ambiguity.

5 Conclusions

This chapter was motivated by the desire for a normative decision theory for environmental policies that accommodates the existence of ambiguity and ignorance. It concludes that SEU has severe limitations as a model for decision making under ambiguity and ignorance. Out of a number of alternative decision theories, a combination of the Dempster-Shafer belief-function theory and Choquet expected utility is suggested as the most suitable model for the purpose at hand. The pessimistic attitude toward ambiguity that is manifest in CEU is the result of a cumulative dominance axiom. If this axiom is considered unacceptable, an incomplete ordering of acts is still possible that is independent of attitudes toward ambiguity. It is shown how the suggested theory addresses many requirements for a suitable model including the representation of ambiguity and ignorance, and the construction and aggregation of beliefs from evidence.

An important conclusion from the discussions in this chapter is that, while CEU is preferable to SEU, there is no strong normative foundation for any model of decisions making under ambiguity and ignorance. Therefore, it would be most important in any decision model to make the treatment of ambiguity and ignorance explicit rather than bury it in assumptions, as it occurs in SEU. The proposed theory allows this transparency by setting bounds on the value function that hold regardless of the assumed attitudes toward ambiguity. Thereby, those decisions that require assumptions about the treatment of ambiguity can be isolated from those that do not. As a direction for further research, it may prove useful to empirically analyze a decision model with a behavioural parameter of optimism about ambiguity.

Hopefully, the suggested theory offers a methodology that will help overcome the deficiencies in the practical evaluation of uncertain environmental costs and benefits. These practical deficiencies are often manifest in ignoring environmental effects altogether. If CEU, and hence the cumulative dominance axiom, is accepted as a normative basis, the implied pessimism about ambiguity would tend to increase the cost or benefits assigned to uncertain environmental damage or improvements. Even if the axiom was not accepted, this chapter shows that there would not be a normative basis for accepting an activity that might be considered acceptable under a decision theory that suppresses ambiguity, such as SEU. Under either condition, the suggested theory would increase the attractiveness of sustainable alternatives to natural capital depletion, such as pollution abatement or compensating investments, since the costs of ambiguous environmental damages would weight relatively higher compared to the risky, but often not or less ambiguous, costs of environmental sustainability.

While the proposed theory overcomes some of the shortcomings of SEU, its usefulness remains to be analyzed in practical situations involving a complex choice problem. At least three problems with the suggested theory deserve further attention. The first problem is that there remains some doubt about the descriptive and prescriptive power of the cumulative dominance axiom. If this axiom is not invoked, and no other assumption about behaviour under ambiguity is introduced, ordering of acts may be incomplete. At this stage, the only suggestion made is to use the behavioural parameter of optimism about ambiguity, α, as a parameter for sensitivity analysis on the given problem. The sensitivity of a decision with respect to the parameter of optimism about ambiguity, α, would have to be explicitly discussed which makes the treatment of ambiguity and ignorance transparent in the decision making process. The weak normative basis for any decision that depends on choice of a specific α, would justify a no-regret approach of not undertaking any activities that generate ambiguity and would be undesirable with at least some α value.

The second problem relates to information that is available but not used in calculating CEU. Evidence about a problem situation is represented in the belief function over all subsets of the set of states. However, the calculation of CEU is not based on the beliefs about all subsets. CEU only recognizes the states resulting in the highest and lowest utility in a subset of states. This means that in the calculation of CEU, a possible difference in beliefs over the set of states $\{\omega_1, \omega_2, \omega_3\}$ and another set $\{\omega_1, \omega_3\}$ is ignored if $u(a(\omega_1)) > u(a(\omega_2)) > u(a(\omega_3))$. With the cumulative dominance axiom for CEU one has to accept that information such as the difference between beliefs in the two sets above is irrelevant to the problem. Similarly, with Savage's axioms for SEU one accepts that the information relating to a probability's reliability is irrelevant to a given problem.

The third concern about the suggested theory relates to the requirement of specifying beliefs over subsets of states and upper and lower bounds for the utility obtained from scenarios. Just as difficult as it is to define an additive probability measure for SEU, it may be difficult to define beliefs and upper probabilities of particular states, in some situation. However, a belief function appears to be a more natural way to express evidence and represent incomplete knowledge of the decision problems. Moreover, eliciting a probability range for a state would be less prone to framing effects and other biases that result from the description of the problem (i.e. the presentation of elementary states or the scale on which outcomes are presented (physical impacts versus dollar versus utility). Also, it is difficult to imagine an approach for considering scenarios unless some bounds can be determined on their utility outcomes. Again, in some decision problems this may still be too rigid a structure. More often, however, it appears that there are natural upper and lower bounds on the impact that a specific act can have, determined by either geographic scale of the act or the number of people that can possibly be effected or the like. The major advantage of putting probability weight for scenarios on the upper and lower bounds only lies in avoiding the arbitrariness arising from assigning weights to intermediate utility values.

CHAPTER IV

A SUSTAINABILITY CONSTRAINT: REQUIREMENTS, SPECIFICATIONS, AND APPLICATIONS

1 Introduction

The purpose of this chapter is to consider the conclusions from chapters I-III and provide a constructive perspective on policies designed to remedy the deficiencies of conventional economic analysis of natural capital depletion. Specifically, this chapter attempts to show how the imposition of a sustainability constraint on the economic activities of the current generation would address the concerns about the deficiencies of market forces to bring about efficient and intergenerationally equitable use of natural capital. While sustainability is an increasingly popular policy objective, there is little agreement on the precise meaning of this concept. Therefore, an additional objective of this chapter is to provide an operational definition of sustainability that can be applied to practical policy making, such as the decision about a resource project. This chapter will show how economic analysis tools, such as cost benefit analysis, that were developed for an almost empty world, can be adjusted in order to be useful for analysis in a full world. The chapter presents a method for evaluation and comparison of projects or policies that involve depletion of natural capital, for example, in the form of depletion of a non-renewable resource, over-exploitation of a renewable resource or exhaustion of the biosphere's waste absorbtion capacity.

Often, detailed formal analysis is required in order to better understand a specific problem. In other cases, a broad and simultaneous view of many issues is required to gain understanding. While the first three chapters have followed the former approach, this chapter follows the latter. In this chapter, I try to assess the aggregate impact of many different effects: those analyzed in chapters I-III as well as others that are not analyzed in detail in this thesis. This chapter attempts to synthesize the discussion of these effects and to explore the limitations and implications of formal economic modeling of natural capital depletion. As a result, this chapter relies less on formal analysis than on summaries and intuitive arguments that seem more appropriate for the material at hand.

In section 2, I will summarize the deficiencies of conventional analysis of natural capital depletion as it follows from the discussions in chapters I, II, and III. It will be shown that, due to various market failures, conventional economic evaluation is likely underestimating the costs of natural capital depletion. It will be argued, based on principles of intergenerational justice, that adequate compensation of future generations for the depletion of natural capital is required. The discussion in section 3 will show how a sustainability constraint would be able to deal with the deficiencies of conventional analysis. Subsequently, a practical approach for the integration of a sustainability constraint with project analysis is suggested. The "sustainable supply rule", proposed in section 4, would allow derivation of a sustainable price for the depletion of natural capital which should be used as the shadow price for natural capital depletion in project analysis. Section 4 also discusses applications of the sustainable supply rule. Section 5 presents a stylized case studies that applies the sustainable supply rule to an oil development project.

2 The Need for a Sustainability Constraint

This section discusses a variety of reasons why the evaluation of natural capital depletion with conventional methods is deficient. In the first part of this section, I will abstract from issues of intergenerational welfare distribution. I will discuss the market failures that lead to deviations of the market price from the economic value of natural capital and the systematic biases against remedying these market failures. Also, the inherent incompleteness of shadow prices for natural capital due to the uncertainty about long-term environmental costs will be demonstrated. The second part of this section will address the special concerns arising from the intergenerational problem with respect to depletion of natural capital. Both parts of this section together demonstrate the need for a sustainability constraint on economic activities which would have to be reflected in economic evaluation.

2.1 Inefficient Market and Shadow Prices of Natural Capital

This sub-section will demonstrate why externalities and the use of a private discount rate that is higher than the social discount rate will lead to inefficient market prices of natural capital. These market failures suggest the need for government intervention. However, in order to design efficient environmental policies, it is necessary to shadow price natural capital. Therefore, the practical deficiencies in shadow pricing natural capital will be discussed. Subsequently, suggestions will be made for a better approach to shadow pricing under uncertainty based on the decision theory proposed in chapter III.

2.1.1 Lack of Reliable Market Prices for Natural Capital

An investor in human-made capital would expect that property rights for the investment are established and that markets exist on which the capital and outputs of the investment can be exchanged, in order to be able to reap the benefits of the investment. Natural capital, on the other hand, exists without an investor to ensure the existence of property rights and markets for such capital. Hence, in contrast to human-made capital, property rights as the prerequisite for the existence of markets do not exist for many types of natural capital. Since markets do not exist traditionally, they would have to be created. Creating markets for natural capital, however, is often prohibitively costly since many types of natural capital provide public goods, and their depletion is associated with negative externalities. Examples include forestry, fisheries, public rangelands, ground-water resources and the waste absorption capacity of air, land, and water. The use of these resources generates external costs that are not considered in individual decision making. Even where property rights can be created, they are often less secure than those for other assets. For example, governments in developing countries may lack the institutional strength to restrict access to natural resources, resulting in inefficient over-usage and under-pricing of the resource.

When the depletion of natural capital is caused by production, and the costs of depletion are not included in the product's price, an environmental externality exists. Externalities can be remedied by, for example, Pigou taxes or the introduction of trade with emission certificates (see Baumol and Oates 1988). However, these instruments are rarely used. Public decision makers seem to have few incentives to implement policies for the internalization of external effects, since they are more exposed to the concentrated influence of internal beneficiaries (the polluter or user of natural capital) than to the dispersed voices of damaged individuals. For a single polluter, lobbying politicians is much cheaper than for a large number of damaged individuals who would suffer from the costs of organizing and coordinating their collective lobbying efforts (see Mueller 1989, pp 235-238, for a review of the pertinent literature on lobbying and government regulation). Facing intense lobbying by the polluters, politicians can use the prevailing uncertainty and the significant information requirement for determining external costs as a justification for delaying efficient policies.

It would be insufficient to remedy recognized market failures only. Even if Pigou taxes were implemented for all known and proven external costs, the long lag from the time environmental damage is caused to the discovery of an environmental problem and to political recognition and action, would lead to systematic underestimation of external costs. Static consideration of policies to internalize externalities neglects dynamic incentives for the generation of external costs. For utility maximizing individuals, profit maximizing corporations and social welfare maximizing local or national governments, there is a systematic incentive to generate internal benefits not only by productive activities but also by shifting costs to external entities. Costs of depletion of natural capital can be shifted to outside individuals, corporations, regions, or countries. This continuous and pervasive incentive to invent new ways of depleting natural capital causes governments to notoriously lag behind in charging a price for the use of natural capital or securing property rights. Together, these factors would explain some of the apparent deficiencies in the implementation of efficient environmental policies and the lack of reliable market prices for natural capital.

The depletion of some types of natural capital, notably some non-renewable resources, is not directly linked to negative externalities. Following conventional resource economic analysis, in a world without extraction costs and with certainty or complete markets, maximizing social benefits from depletion of a non-renewable resource would require depletion at a rate such that the price of the resource rises at the marginal rate of return to investment in the economy (see Hotelling 1931). Similarly, the price of a renewable resource would have to change with the rate of return minus the natural rate of growth of the resource. The initial price for a non-renewable resource (or a renewable resource with a growth rate below the interest rate for all stock levels) would be set such that the resource is depleted exactly at the time when the rising price reaches the cost of a backstop technology, or demand is reduced to zero. The inter-temporal resource allocation, resulting from the Hotelling rule, would be efficient since rents derived from the resource could be invested at the rate of interest such that no other resource depletion path would Pareto-dominate the outcome. In a world with perfect and complete markets for natural capital, this efficient result would be brought about by the market mechanism.

Perfect and complete markets, however, are unlikely to exist. Chapter II has shown that complete markets are, in fact, impossible due to the intergenerational structure of the problem. Even if perfect markets for a natural resource existed and no obvious externality prevailed, the market price would underestimate the social opportunity cost of resource depletion if the private discount rate of resource owners exceeds the social discount rate. The opportunity cost of depletion (the user cost) is the discounted future benefit foregone because of depletion. Hence, the user cost depends on the discount rate used by the decision maker. If the decision maker uses a discount rate higher than the social discount rate, the resource would be depleted too fast and prices would be less than the social opportunity cost. An extensive body of literature deals with the complex question whether private and social discount rates do or do not coincide (for an overview of the issues see the introduction in Lind et al. 1982). The main arguments for a difference between the two rates are based on differences between social and individual risk, taxes, and capital market imperfections. Here, I will highlight only some of the concerns suggesting that the decision maker's discount rate is likely to exceed the social discount rate. The first group of arguments suggests that the discount rate of profit maximizing resource owners is above the social discount rate. The second group of arguments suggests that individual decision makers apply a discount rate higher than the discount rate of a profit maximizing resource owner.

First, the discount rate of profit maximizing resource owners will be excessive if private marginal rates of return on investment exceed social rates of return. In the real world, the social return on investment would be below private returns because of the existence of external costs that are not internalized for the reasons discussed above. In general, investment in natural capital seems to be more associated with external benefits (such as a forest that provides external benefits in the form of recreational value, climatic stabilization, soil stabilization and habitat for wildlife) while industrial investment produces primarily external costs (such as pollution and waste products of an industrial plant). Incomplete internalization of external effects means that market forces would equalize private but not social rates of return on investment. With declining marginal rates of return, this would lead to excessive industrial investment and insufficient investment in natural capital compared to the social optimum. The private discount rate would be well above the social rate of return on investment. Note that this argument is based on the existence of negative externalities from general investment in the economy, not necessarily from depletion of the natural resource.

Second, market interests rates are based on the decisions of short-living individuals who exhibit a positive rate of pure time preference or impatience (the rate at which future utility is discounted). However, for the consideration of the social discount rate, it would be inappropriate to extrapolate from pure time preference over the short lifetime of an individual to intergenerational time. While a moderate variation of well-being during an individual's lifetime would be rationally accepted, the same rate of pure time preference applied to very long time periods would imply acceptance of extreme hardship during later times for moderately increased well-being earlier on. The extrapolation of pure time preference to periods that exceed human lifetime seems inappropriate. Social time preference would, therefore, be lower than individual pure time preference.

Third, private discount rates are based on the consideration of risks that are absent from a social point of view. Private discount rates would be excessive due to the risk of appropriation and the instability of property rights for natural resources. Private owners of a resource provide for the risk of restrictive government regulation by increasing extraction and, implicitly, using a higher discount rate. This implicit discount rate would be above the social discount rate since resource appropriation, would merely imply a change of ownership and not represent a social risk that requires discounting. In addition, market interest rates reflect the individual risk of death and the resulting uncertainty of future consumption. This leads to higher discounting of future consumption. On the other hand, social discounting should only reflect the corresponding, but much lower, risk of extinction. However, the risk of extinction of the human species is, at least in part, endogenously determined by the activities and the discount rate used by the present generation. Discounting for an endogenous risk of extinction could justify the present generation's deliberate decision to be the final generation and deplete all natural capital. Assured extinction after the present generation would justify a zero weight on future consumption (equivalent to an infinite discount rate). This would deny future generations their right to existence and strongly violate our ethical intuition. Social discounting on the basis of endogenous risk of extinction is, therefore, unacceptable.

Finally, capital market imperfections can lead to resource owners under financial distress depleting a resource excessively, implying a discount rate above the social rate. A company under financial distress, facing risk of bankruptcy, may disregard the opportunity costs of depletion in order to avoid the costs of bankruptcy and reorganization. Similarly, a country under a foreign exchange constraint may choose to increase depletion and export of natural resources at a depressed price. This would explain the increased, and from a global perspective inefficient, liquidation of natural capital in several highly indebted developing countries in recent years.

The second group of arguments why decision makers would apply a discount rate higher than the social discount rate is based on evidence of resource owners' behaviour that is inconsistent with profit maximization. When resources are owned by governments, extraction licenses are often granted through tender and bidding procedures that do not take inter-temporal welfare maximization into account and encourage excessive extraction. Behaviour of decision makers that is inconsistent with profit maximization can be explained by the principal-agent problem, or the conflict of interest, between the owner of the resource (a country or a company) and the individual decision maker (a manager or politician). Individual incentives may lead to explicit manipulation of decisions, however, more likely is a subtle but systematic bias in the decision making of government, companies and lending agencies.

If politicians use GNP figures, or other related income measures that omit accounting for natural capital depletion (see Ahmad et al. 1989) as signals of their performance to the electorate, they would have an incentive to maximize GNP rather than, unobservable, social welfare and, hence, encourage excessive resource depletion. Similarly, the manager of a company who knows more than the shareholders about the value of the natural resource owned by the company would have an incentive to underestimate future opportunity costs in order to boost present profits and his own corresponding compensation. Also, managers of lending agencies that decide about the funding of resource projects often face incentives that are biased toward achieving short-term benefits due to the difficulties of any system of personal long-term accountability. The incentives of project managers may explain why the cost-benefit studies of extraction projects often do not include a user cost. For example, the World Bank frequently includes the full resource rent as a benefit in the calculation of economic rates of return for extraction projects (see von Amsberg 1993). Hence, under the conditions that, first, decision makers within an organization maximize not benefits to the organization but personal utility, second, their tenure is shorter than the time span over which their decisions have effects and, third, information is incomplete, there would be a systematic incentive to undertake activities that generate benefits in the present and costs in the future even if discounted future costs outweigh present benefits. Since information imperfections can be especially severe for future opportunity costs which are often less visible than financial costs, which are reflected in financial statements, opportunity costs may be hidden from the principal (the shareholders or the electorate) relatively easily. If project economists, managers and politicians ignore or underestimate user costs, the supply of extracted natural resources will be higher then in the efficient market equilibrium. In aggregate, this effect is likely to be non-marginal and would depresses market prices for natural resources.

In summary, markets for natural capital often do not exist due to the lack of property rights. Policy makers seem to have little incentive to implement efficient environmental policies to internalize externalities. Even if policy makers desire implementation of efficient policies, it is difficult to establish markets for natural capital due to the pubic good nature of many natural resources and dynamic incentives to use natural capital in increasingly pervasive and evasive ways. Even when markets for natural capital exist, market prices are likely underestimating economic values since decision makers often have individual incentives to ignore opportunity costs and use an implicit discount rate above the appropriate social discount rate.

2.1.2 Difficulties with Shadow Pricing Natural Capital

For many environmental policies, such as setting environmental standards or taxes, or evaluating a project that depletes natural capital, an estimate of the economic cost of natural capital depletion is required. Due to the discussed distortions of market prices, the depletion of natural capital needs to be shadow priced. The correct shadow price is the opportunity cost of natural capital depletion, or the value of natural capital in its next best alternative, present or future use. Determining this shadow price is a complex task since for global resources (such as oceans, atmosphere), non-tradable resources (such as forests) and even tradable resources evaluated from a global perspective (maximizing social welfare on a global and not a national level), the best of all possible alternative uses, now or at any time in the future, has to be determined in order to be able to shadow price the resource. If the depletion of a tradable resource is evaluated from a national point of view, the expected international price of the resource, after depletion, has to be estimated.

The opportunity cost of depleting a stock of a non-renewable resource is generally recognized as the user cost which is the discounted value of future benefits foregone through current depletion (see Hotelling 1931). The applicability of the opportunity cost concept to other types of natural capital depletion is often neglected (see also Akerlof 1981). Any depletion of natural capital that excludes or diminishes the potential benefits from identical or alternative activities, now or in the future, implies a social opportunity cost that should be reflected in the shadow price. Consider, for example, an emission generating factory that due to low levels of emission does not cause any environmental damage. If a second factory was economically feasible but would lead to environmental damage due to the aggregate emissions of both factories, the first factory would have caused a social opportunity cost which, for efficiency reasons, should be allocated to that factory as a user charge for a non-marketed production factor. This non-marketed production factor is natural capital in the form of the limited absorption capacity of the natural environment. As this example with discrete investment opportunities shows, a social cost for using the environment can occur even in the absence of environmental damage. This broader view of the opportunity cost concept highlights the pervasiveness of external costs of economic activities in industrial economies and demonstrates that many "free goods" are in fact not free but valuable natural capital.

The problems with shadow pricing natural capital depletion can best be illustrated by examining shadow pricing practice in cost-benefit analysis. For that purpose, I have previously analyzed the economic evaluation of several World Bank projects that deplete natural capital (von Amsberg 1993). Many World Bank economists have made important contributions to the natural resource economics literature, and the World Bank is a recognized leader in the development and application of cost-benefit analysis techniques. It is striking, therefore, that in most World Bank project evaluations natural capital is treated as a free good. Thus, the depletion of natural capital is not treated as a cost. This deficiency is most noticeable for the evaluation of natural resource depletion, land use and emissions.

In most projects that involve depletion of a natural resource, such as mining or oil/gas projects, no user cost or depletion premium is included in the calculation of economic project costs. For example, a gas extraction project would be evaluated as if the project actually produced natural gas while, in fact, it is merely depleting a natural gas reservoir. In some cases, a depletion premium is calculated, however, the opportunity cost of depletion is discounted at a rate higher than the assumed increase in real prices of the in-situ resource. This approach leads to a negligible depletion premium and is inconsistent with efficient markets, which would lead to the user cost of a specific in-situ resource rising at a rate equal to the opportunity cost of capital.

In many World Bank project reports, the opportunity cost of land is assumed to be zero, often with the justification that there is no alternative commercial use for the land. For projects that not only use but also degrade land (as is the case with many agricultural and mining projects), this assumption is clearly questionable. Most land serves many functions beyond their obvious commercial use, including use for various subsistence activities, and recreation. Moreover, in an increasingly crowded world, many remaining wilderness areas are important for preserving biological diversity.

Also, the costs of atmospheric emissions are usually not quantified in the economic analysis of projects even though possible damage from emissions is often acknowledged in the reports. Carbon dioxide emissions are not even mentioned in most of the analyzed reports. Two justifications for not including damage costs from emissions are often given, but should be rejected. First, for almost all pollutants there is considerable uncertainty about the damages arising from emissions. As a result, a quantification and evaluation of damage is often not attempted. Omitting damage costs from the analysis implies the assumption of zero damage costs. Assuming zero costs because of uncertainty is an obviously undesirable practice. Second, many projects include some pollution abatement measures. Even if the remaining emissions do not exceed international emission standards, damages arising from these emissions need to be considered. If emission standards were set efficiently, marginal abatement costs would be equalized with marginal damage costs. Hence, damage arises even in the presence of an efficient pollution standard. While the adherence to pollution standards is commendable, it does not alleviate the requirement to evaluate damage arising from emissions within given standards. Both, abatement costs and damage costs arising from remaining emissions need to be included in a complete economic analysis.

All the examples of deficient practices have in common that shadow pricing of natural capital is seriously impaired by the fact that the services rendered by natural capital are pervasive and difficult to evaluate completely. The opportunity cost of clear-cutting a forest includes all benefits that could have been derived from the standing forest. These include recreational benefits, climatic stabilization, return on sustainable forestry and others. While the number of effects to be considered and the information requirements may be overwhelming, more problems arise because of limited knowledge about the functioning of the biosphere. The costs of releasing CFCs into the atmosphere could not have been correctly evaluated twenty years ago because the destructive effects of CFCs on the ozone layer were not yet known. Moreover, there is great uncertainty about cultural and technological development of humanity; hence, the economic value of resources in the distant future is almost impossible to estimate. Too many unexpected events and potential discoveries lie ahead to make sensible point estimates of resource values hundreds of years ahead. As a result, practical evaluation of the opportunity costs of natural capital depletion is often incomplete since only those effects that are already known and understood are included. Our knowledge that there are potential, yet unknown, costs of depletion is not reflected. Thus, conventional shadow pricing of natural capital depletion implies a systematic underestimation of depletion costs. The benefits from depletion, on the other hand, are evaluated more or less completely since they are usually captured by the market for output products, such as steal, pulp, electricity, or others.

Shadow pricing techniques that are more sophisticated than those used in practice are available. For the evaluation of risks, the option value concept has been developed (see Cichetti and Freeman 1971). Irreversibility can conceptually be included by adding a quasi-option value (see Arrow and Fisher 1974).[1] However, sophisticated evaluation techniques are rarely used in practice due to the high information requirements and the involved effort that does not seem to be justified in light of general data imprecision. Moreover, all these techniques have conceptual limitations since they are based on subjective expected utility theory and, subsequently, do not appropriately deal with situations of ambiguity and ignorance (see chapter III) even though ambiguity and ignorance are most important for the costs of natural capital depletion.

2.1.3 A Better Default Value for Natural Capital

Consider the extreme case of complete ignorance about the cost resulting from depletion of natural capital. I will call the cost assigned to depletion under complete ignorance the 'default value'. The current practice of evaluation is based on positive enumeration of those costs that are already known; hence, the default value of natural capital is zero. Already, a good Bayesian decision maker would reject current practice. The neglect of natural capital in economic evaluation strongly conflicts with our understanding that the earth's natural capital is a proven system resulting from millions of years of evolution that provides life support for humans. This argument is based on the view of natural capital not as an arbitrary accumulation of natural resources but as a complicated web of interactions that has emerged from evolutionary competition. Therefore, there is a good chance that any interference with this system causes a cost to humans that a Bayesian decision maker would take into account even if the precise mechanism by which this cost is generated is not completely understood. Past experiences of unexpected negative consequences of interference

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[1] The environmental economics literature uses the term 'option value' for what is usually referred to as a risk premium. A 'quasi-option value' in environmental economics would be called an option value in financial economics.

with natural systems (ozone layer depletion, greenhouse effect etc.) would suggest that a cautious approach with respect to depletion of natural capital is in our best interest. Such a cautious approach would reflect the expectation of unpredictable costs arising from the depletion of natural capital.

The problems of analyzing costs under ambiguity and ignorance have been discussed in chapter III. According to that discussion, a belief function would be a more appropriate representation of uncertainty than the subjective probability distribution a Bayesian decision maker would use. The proposed decision theory, based on Choquet expected utility (CEU), would lead to a more cautious approach in the evaluation of natural capital depletion. Under complete ignorance, the cost assigned to depletion would be the maximum of the range of possible costs. This highest possible cost would be the cost of offsetting the damage (providing a sustainable substitute or implementing measures that mitigate any damage to natural capital). Hence, the default value of natural capital would be the cost of offsetting any damage (I will refer to this as the cost of a sustainable substitute from here on). The suggestion for evaluating natural capital at the cost of a renewable substitute goes back to John Ise (1925). Even if the normative basis for CEU is not accepted, the discussion in Chapter III shows that, in face of complete ignorance, there are no normative grounds for accepting a decision that is based on a lower value of natural capital depletion. The resulting approach reflects the view that we do not fully understand the functioning of the natural systems; therefore, natural capital in its original form deserves considerable benefit of doubt for its existence.

Implementation of a more cautious approach to natural capital depletion would not imply that all natural capital must be left untouched. Rather, the pessimistic attitude toward ambiguity, implicit in CEU, leads to a reversal in the burden of proof. Current practice implies that natural capital should be depleted unless it can be shown that depletion makes us worse off. A cautious approach would require that natural capital be left intact unless it can be shown that depletion makes us better off. The difference can be significant in a world of large uncertainties. Life on earth has emerged from co-evolutionary adaptation to the current composition of the atmosphere. Hence, changing the composition of the atmosphere is likely to disrupt the functioning of the biosphere in fundamental ways. Therefore, it would be acceptable to change the composition of the atmosphere (for example through excessive carbon dioxide emissions) only if we understood the functioning of the biosphere sufficiently well to be able to show confidently that a change in the composition of the atmosphere would make us better off. On the other hand, current practice would suggest to pollute the atmosphere until we find out that the damage, which results from this change, outweighs the benefits. We are currently learning about the functioning of the biosphere by trial and error. However, due to the increased human population and our ability to amplify our impacts on the environment through technology, the stakes of this trial and error have grown so large that it is now generating unacceptable uncertainty. Moreover, many forms of natural capital depletion, and thus our possible errors, are irreversible. This increases the risks and provides additional support for a cautious approach and a reversal in the burden of proof.

While CEU suggests that the default value for resource depletion would be the cost of a sustainable substitute, we can, step by step, reduce this value as our knowledge about the functioning of the world increases, and we conclude that it is to our benefit to deplete natural capital. The theory presented in chapter III would be used to evaluate the depletion cost at every stage in this learning process. This is in contrast to current practice that would begin with a default value of zero for a presumably free good. As unexpected damage arises, or the resource becomes scarce, the cost of natural capital depletion would be increased step by step. Once uncertainty is resolved, the resulting value assigned to natural capital is the same under either approach. The difference is that during the learning process, under the cautious approach, the true value of natural capital depletion is approached from a higher value. The cautious approach leads to a reversal of the default assumption of natural capital as a free good to the assumption that every unsustainable activity must bear the cost of its conversion to a sustainable activity.

Some examples can illustrate this change in the default assumption. For the evaluation of an oil field's depletion, the cautious approach would imply initial pricing of the energy resource at the cost of a sustainable substitute, such as solar energy. This shadow price would be reduced if it can be shown with reasonable confidence that depletion does not cause unexpected environmental damage, that there are no alternative future high-value uses for oil, and that depletion makes us better off. A renewable resource, such as a forest would be priced according to the sustainable yield at a desired stock level. Cutting trees beyond the sustainable yield would be acceptable only if it can be shown that all costs arising from reduction of the forest are outweighed by the benefits. If a sustainable substitute for natural capital does not exist, the default value for depletion would be the maximum possible damage. The extinction of a species would carry an infinite cost unless its future value can be bounded from above. This cautious approach can help avoid large costs that arise if an alternative high-value use is discovered after a resource is depleted. For example, sustainable yield forestry would have reduced the loss of a large numbers of Pacific Yew trees that were only recently discovered to contain the ingredient for a potent cancer fighting drug ('Taxol'). If the future value of a non-renewable resource is known with some confidence, depletion would be acceptable at a price that provides for compensation of the opportunity cost imposed on the future.

2.2 The Intergenerational Problem

The depletion of natural capital has impacts that reach beyond the time span of one generation. Chapter II has shown inefficiencies arising from natural capital depletion under uncertainty in an intergenerational context. Other intergenerational market failures will be discussed in this section. Chapter I has shown problems of intergenerational welfare distribution that result from natural capital depletion. Both types of intergenerational problems are examined in this section, leading to the definition of requirements for overcoming the intergenerational inefficiencies and the distributional concerns.

2.2.1 Intergenerational Market Failures

It was already discussed in an intra-generational framework, that there is inefficiently high depletion of those types of natural capital that have the attributes of a public good. In many cases, the costs of natural capital depletion will be realized only years or decades ahead. In an intergenerational context, the externality problem is aggravated by the fact that the damaged future generations are not represented in the political decision making processes that could remedy the externality problem. Hence, individuals of the current generation do not only have an excessive incentive to deplete natural capital but also do not have a collective incentive to curtail depletion to efficient levels since the costs of depletion are imposed on future generations as an externality. While it is fairly obvious that pollution and some other types of natural capital depletion generate externalities, there are other, less obvious, types of intergenerational externalities that lead to concerns about the efficiency of markets across generations. An example would be investments that yield long-term returns that are inherited by future generations, such as large public projects (a dam or a subway system) or economy-wide learning-by-doing effects (see Arrow 1962). In these examples, early generations would not undertake efficient investments because the returns are realized only to future generations. This diffusion of benefits to future generations leads to a market failure similar to those failures that are well recognized for research and development investments in the intra-generational context (see Tirole 1988, pp. 389-419, chapter 10).

Chapter II has analyzed another type of intergenerational market failure. Intergenerational insurance markets are necessarily incomplete since no generation can participate in trade before it is born. Therefore, markets do not bring about efficient intergenerational allocation of the risks that are arising from natural capital depletion. Chapter II has shown that there is an excessive incentive to deplete natural capital (i.e., reduce the diversity of species) if the resulting risk is primarily born by future generations. Similarly, there is an insufficiently low incentive to invest in sustainable substitutes that reduce future risks from the depletion of natural capital. On the other hand, incentives to invest into activities with risks that could be diversified across generations are inefficiently low.

In these examples of intergenerational market failures, a coordination mechanism between generations could make all generations better off. Such a coordination mechanism would lead to the first generation taking certain actions, such as investing in building a dam, in return for the second generation honouring an implicit intergenerational contract (it cannot be an explicit contract since the second generation is not yet born at the time this contract would have to be closed), such as paying for the dam. While such a contract would make all generations better off, the second generation does not have an ex-post incentive to honour it. Alternatively, an implicit intergenerational contract may allow the first generation to impose an external cost on the second generation if the former compensates the latter for this cost once the second generation is born. In this example, the first generation would not have an incentive to honour the contract. In both cases, legal and institutional barriers, such as debt arrangements could prevent generations from repudiating the contract. Note that many social security systems operate on a pay-as-you-go basis. Their functioning is obviously based on a similar implicit intergenerational contract. The two elements of the suggested intergenerational contract would be a mechanism to compensate another generation for imposed external effects (costs or benefits) and a mechanism to equalize risks across generations (equalize the ratio of marginal utility between different states of the world).

2.2.2 The Problem of Intergenerational Welfare Distribution

The analysis in chapter I has shown that problems of intergenerational welfare distribution lie at the heart of the problem of natural capital depletion. This section does not attempt to deal comprehensively with the complex philosophical questions involved in intergenerational choice. Only some important concerns of relevance to the evaluation of natural capital depletion will be discussed here (see Berry 1983 for a broader discussion). In chapter I, the public good nature of caring for future generations was discussed. Here it is assumed that, in their individual choices, generations do not consider the impacts of their decision making on the welfare of future generations. This section summarizes some results from chapter I and suggests an intuitive requirement for a rule that would lead to equitable intergenerational welfare distribution. The imposition of such a rule can be seen as one approach to collective action in order to overcome the public good problem of caring for future generations.

Practical economic analysis usually emphasizes the efficiency aspects and disregards the possible distributional impacts of activities that deplete natural capital. Projects, for example, are commonly evaluated according to the potential Pareto criterion (also referred to as the Kaldor or compensation criterion). This criterion states that an activity should be undertaken if those who gain from the activity could compensate those who lose and still be better off. Since hardly any project is conceivable that does not lead to losses for at least some individuals, projects are justified on efficiency grounds even though they only achieve a potential Pareto improvement and not an actual Pareto improvement. The use of the potential Pareto criterion is quite justifiable in cases where no individuals suffer large losses from a project, where effective income redistribution mechanisms are in place and where no systematic bias exists against any group. Under these circumstances it can be expected that compensation can be implicitly achieved by the sum of all projects which in aggregate would provide net benefits to every individual.

The depletion of natural capital often imposes costs on future generations. In these cases, the conditions that would justify use of the potential Pareto criterion are unlikely to be met. Large losses to specific generations may be possible because long-term discounting diminishes the impact of even catastrophic events in the future (i.e. a nuclear accident). There is no reason to assume that the income distribution between present and future generations is explicitly endorsed. Furthermore, the decision not to compensate losers can be reversed within the same generation. In intergenerational choice, however, gainers will have died by the time losers live. Hence, the decision to not actually compensate is irreversible. Also, the selection of projects by the current generation would be systematically biased in favour of projects benefitting the current and burdening future generations. For these reasons it was suggested by Page (1983) to exclude intergenerational problems from evaluation with the potential Pareto criterion. Concentration of economic analysis on efficiency may be justified for intra-generational choice because of the existence of effective mechanisms to bring about the socially desired income distribution through government transfer payments. In intergenerational choice, on the other hand, there is a fundamental asymmetry between present and future generations since distribution of resources is determined by the present generation alone. Future generations have no influence on current decisions. A pure efficiency criterion could, therefore, not prevent any single generation from consuming all resources leaving future generations uncompensated. Hence, intergenerational justice needs to be explicitly considered.

The analysis in chapter I, building on work by Howarth and Norgaard (1990), shows in a general-equilibrium model with overlapping generations that for every possible distribution of resource ownership across generations, there is a different efficient depletion path. Market prices would be correct indicators of economic value only if the implicit assumptions about inter-generational resource distribution were considered socially acceptable. However, an increase in the share of the resource owned by the first generation unambiguously increases welfare of the first and reduces welfare of the second generation. Hence, a self-interested first generation would assume ownership of the full resource stock, leading to gloomy welfare levels for future generations even if the resource is depleted efficiently. The channelling problem described in chapter I aggravates this income effect. There is an additional income effect against the welfare of future generations arising from the depletion of non-marketed types of natural capital (negative externalities). A systematic incentive for the current generation to generate current benefits at the expense of future costs, leads to additional concerns about future generations' welfare even if the actions of the first generation are efficient.

Preferences about the desired intergenerational welfare distribution can be expressed in an intergenerational social welfare function that reflects the desired ethical position. One conceptual approach for choosing a social welfare function has been suggested by Rawls

(1971). The conflicting interests of different generations would be assessed by those generations behind a "veil of ignorance", meaning that individuals would have to decide on a social welfare function without knowing which generation they are going to be part of. Rawls suggests (specifically in an intra-generational context, though) that a maximin welfare function would be chosen under these circumstances. Yet, it is difficult to imagine that consensus on a social welfare function could be achieved, in particular since Arrow (1951) has shown that it is impossible to construct a social welfare function based on individual preferences that meets some basic intuitive requirements. If agreement could be found on a social welfare function, the optimal distribution of resources to different generations could be derived from it. However, a social welfare function is hardly operational in an intergenerational context. On top of uncertainty about the impacts of earlier generations' decisions on the consumption opportunities of later generations, there is uncertainty about the preferences of future generations. With the assumption that preferences of future generations are like those of the present generation, the present generation would unduly restrict future choices. Other assumptions about future generations' preferences would be completely arbitrary. More operational than a social welfare function would be Page's (1983) suggestion to require equal opportunities for every generation rather than a specified level of welfare.

It is fairly obvious that the assumptions made by a selfish current generation about resource distribution would be unacceptable and future generations would need to be explicitly compensated for the depletion of natural capital. However, since consensus on a social welfare function appears illusive, and the allocation of resource property rights based on a social welfare function would not be operational, the intergenerational welfare problem will instead be approached by attempting to define rules that are intuitively appealing based on Page's notion of equal opportunities for all generations. The details of applying these rules would depend on specific circumstances and will be discussed later. First, every generation can use natural capital without depleting it. This would include harvesting the sustainable yield from renewable resources and using the environment as a sink for wastes within the natural capacity for regeneration. Second, compensation of all future generations would be required for any depletion of natural capital since depletion excludes the use of natural capital by any future generation. The precise nature and quantity of such compensation will be the topic of much of the remainder of this chapter. However, two intuitively appealing requirements for adequate compensation can be established that would let all generations accept the compensation as a substitute for the depleted natural capital. First, the benefits derived from depletion of natural capital should be shared equally among the depleting and all future generations. Second, a later generations must receive compensation at least equal to the benefits it would receive if this later generation itself, and not earlier generations, depleted the resource and compensated all following generations. This latter condition is meant to restrict wasteful uses of a resource that would be acceptable under the condition of equal rent sharing alone. I will call compensation of future generations that meets these requirements adequate compensation.

Under these rules for intergenerational resource distribution, the endowment of every generation would include the sustainable yield of the earth's natural capital plus the benefits from depletion of natural capital if adequate compensation is made to future generations. This requirement of explicit compensation for any unsustainable use of natural capital would imply a major change in our cultural and legal understanding of ownership of land and other natural resources. This is consistent with the conclusion that not all natural capital can be owned by the current generation for reasons of intergenerational justice. Owning natural capital would only include the right to harvest its sustainable yield while leaving its capital value intact. For example, owning a mine would imply the right to exploit the resource only if adequate compensation of future generations was provided. Land and resource ownership would become comparable to trusteeship rather than to ownership as understood for human-made capital.

3 The Appropriate Sustainability Constraints

Most normative models of economic policies are based on the objective of social welfare. Since social welfare is neither observable nor directly measurable, all economic policies to maximize social welfare are based on some implicit or explicit model of social welfare. Such modeling leads to two problems. First, as discussed there is no consensus on a normative basis for either an intergenerational social welfare function, in particular under uncertainty, or decision making under ignorance and ambiguity, which is pertinent for the problems discussed here. Second, the involved problems are of such complexity that a complete model would exceed individual and institutional processing capacities. As a result, a normative basis for decision making has to be assumed, and the model requires significant abstractions from reality. The discussion in section 2 has shown how these two steps lead to a significant biases against the welfare of future generation, in favour of depletion of natural capital.

Since there is currently no basis for a consensus on either the normative assumptions on which decisions should be based, or the nature of the abstractions that are necessary to obtain an operational model, the decisions that are made should be robust to different models of social welfare. The requirement of robustness means that our decisions should perform relatively well for a variety of reasonable models of the world, at the cost of maximum performance if the one model selected by the decision maker turns out to be the right one. Therefore, maximizing social welfare subject to a constraint that guards against mistakes that can result from incorrect specification of the model may be preferable to maximizing a well specified social welfare model. The introduction of such a constraint is the route suggested to alleviate the deficiencies discussed before, and will be discussed throughout the remainder of this chapter. The imposition of a constraint itself is not based on maximization, but it follows from the recognition of the limits of formal modeling in a complex world. It reflects a strategy of reducing possible regret about decision making based on maximizing an incorrectly specified model. Of course, if one day one could agree on a well specified model of the world, welfare would be higher without the imposition of such a constraint, which would then no longer be appropriate.

In fact, some agreement appears to be emerging that a sustainability constraint on current economic activities is the preferable approach to addressing the intergenerational problem (see Markandya and Pearce 1988, p.42). A sustainability constraint would offset the discussed systematic biases of decision makers against considering opportunity costs and against actually compensating future generations. A sustainability constraint would become part of the framework within which economic analysis takes place. The constraint would exclude economic activities that impede on basic rights of future generations, just like basic individual rights are often considered immune to economic analysis. Within a sustainability constraint, standard economic analysis based on efficiency would be fully applicable.

In this section, I propose a sustainability constraint on current economic activities that addresses the deficiencies of markets and conventional shadow pricing practices to bring about an efficient and intergenerationally equitable use of natural capital. Three main requirements followed from the discussion in section 2. First, due to the inherent incompleteness of conventional evaluation and the lacking normative basis for decision making under ignorance and ambiguity, the default assumption of natural capital as a free good should be reversed, and natural capital depletion should be evaluated at the cost of a sustainable substitute unless it can be shown that the economic costs of depletion are less. Second, to alleviate intergenerational market failures, a mechanism is required that would compensate a generation for external effects imposed by another generation, and equalize risks across generations. Third, concerns about intergenerational welfare distribution suggest compensation of future generations for the depletion of natural capital and equal sharing of the benefits derived from depletion. In this section, a sustainability constraint on economic activities will be discussed that would address these three requirements.

The purpose of a sustainability constraint is to restrict current economic activities by requiring that the current generation leave assets (human-made capital as well as natural capital) behind such that a specified variable, such as consumption or utility, can be maintained at its current value in perpetuity. Various definitions of sustainability have been proposed. Pezzey (1989) discusses a variety of different sustainability definitions. These definitions differ mainly in the variables to which a sustainability constraint is applied. The controversy between proponents of different sustainability constraints is based on different assumptions about the nature of substitutability between different types of assets. Daly and Cobb (1989) discuss the distinction between strong and weak sustainability. A weak sustainability constraint requires the sum of the values of natural and human-made capital stocks to be kept non-declining. Compensation for natural capital depletion would be investment in any other form of capital of equal value. On the other hand, a strong sustainability constraint would require non-declining stocks of human-made and natural capital, separately. Compensation for the depletion of natural capital would have to be made through investment in natural capital. This section suggests a systematic approach to the classification of different sustainability constraints and discusses the appropriateness of different constraints.

3.1 Strong and Weak Sustainability

The difference between strong and weak sustainability can be explained with the diagram in Figure 4.1. The stream of human welfare, depicted at the top of the diagram, is the ultimate concern of the economist with an inherently anthropocentric point of view. The weakest sustainability constraint would apply at this highest level of aggregation. It would require that all human-made and natural capital together be kept intact such that it can support a non-declining stream of welfare in perpetuity. The concept of human welfare is eminently detached from the physical realities of natural capital. Welfare is the result of a variety of consumption streams that are combined in a welfare or utility function. Two representative consumption streams that contribute to welfare are shown at level 2 in Figure 4.1. Questioning the substitutability between different consumption streams, the next stronger sustainability constraint would apply to the different consumption streams separately. This sustainability constraint would require that groups of capital that generate different consumption streams be kept intact, such that they can support consumption streams that are all separately non-declining. Similarly, consumption streams are created by a production process that combines various commodities. Level 3 would represent sustainability of the supply streams for production. Finally, the strongest sustainability constraint (level 4) would apply at the level of extraction of physical assets. This strongest sustainability constraints would require that the stock of specific assets be left intact as to be able to provide non-declining extraction streams.

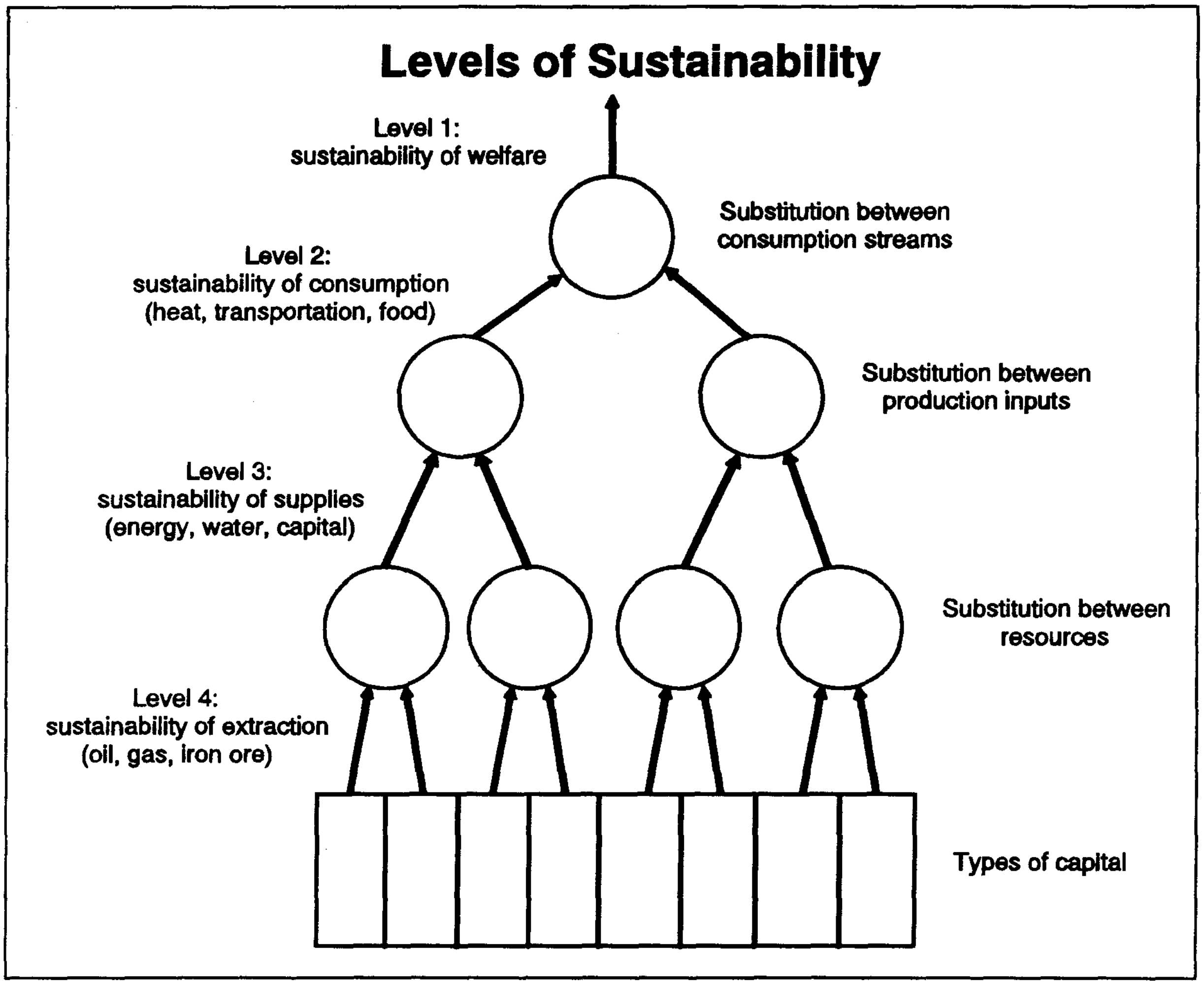

Figure 4.1 Levels of Sustainability

The four discussed levels of sustainability are representative steps along the continuum between the abstract concept of human welfare and the physical concept of individual resource stocks or assets. They represent a decreasing level of abstraction and an increasing proximity to physical realities. Clearly, a sustainability constraint imposed at a higher level of aggregation and abstraction restricts the choices of the living generation less than a sustainability constraint imposed at the level of individual resources. The strong constraint requires to leave capital intact such that a large number of extraction streams can be maintained non-declining separately. The weak constraint, on the other hand, allows for a variety of substitution possibilities and only requires maintaining the welfare stream to be non-declining. The four representative sustainability constraints (non-declining welfare, non-declining consumption streams, non-declining input supply streams and non-declining extraction streams) and their applicability are discussed in more detail in the following paragraphs.

The weakest sustainability constraint (level 1 in Figure 4.1) requires that every generation limits its activities such that a non-declining level of utility can be obtained by all future generations. Under certainty, every generation would deplete resources such that this constraint holds with equality. The maximin welfare path would be the result. Hartwick (1977) and Dixit et.al. (1980) have shown in models with one infinitely living generation that the maximin welfare path would be obtained if net investment in the economy was zero at all times, meaning that all competitive profits from resource depletion are invested in reproducible capital (this is Hartwick's rule). Hence, to meet the sustainability constraint, every generation would be required to invest all resource profits and leave this investment behind as compensation for future generations. In an intergenerational world, the price path would have to be administered such that the resource is depleted efficiently under such constraint (see chapter I). There would be no restriction on the type of compensating investment.

Under certainty, the weakest sustainability constraint would be the appropriate one since future economic prices of all goods and all forms of capital could be predicted. If the stock of all capital, aggregated at real future prices is non-declining, utility would be non-declining and a weak sustainability constraint should suffice. However, the uncertainties involved in long-term forecast of economic prices are numerous. Uncertainty about the economic value of goods in the future can result from demand or supply uncertainty. Demand uncertainties can result from changes in income through differing income elasticities. Unexpected development of technological substitutes or additional uses for goods will change demand. Also, preferences of individuals may change, particularly in the long-term. Supply uncertainty can be caused by changes in technology, changes in the quantity of known natural resource deposits or changes in knowledge about natural system characteristics, such as the regeneration capacity of the atmosphere. Considering non-quantifiable uncertainty such as the possibility of drastic technological advances, cultural changes or catastrophic events, it is clear that ambiguity and ignorance prevail about future prices.

In the absence of reasonable estimates of future economic prices, the weakest sustainability constraint would have to be based on aggregation at present prices. However, using present prices for the valuation of future capital stocks is inappropriate since prices are measures of marginal rates of substitution while depletion of natural capital at the current scale clearly implies non-marginal changes in the economy. Such non-marginal changes will lead to changes in relative prices, not only of non-renewable resources. Investment at present prices is, therefore, unlikely to provide adequate compensation. For example, compensation of future generations for the depletion of oil reserves through investment in a highway system and gasoline-powered vehicles at their present economic values would clearly be inadequate. Gasoline-powered vehicles and oil are complements and their future values are likely to be negatively correlated. In case oil turns out to be very valuable in the future, a high compensation for earlier depletion would be required, however, the vehicles or the highway system, intended to serve as compensation, would be worthless since there is not enough oil to use them. Alternatively, if oil proves to be not as scarce as expected, the earlier generation would have compensated excessively and restricted their own consumption unduly.

Under the multidimensional uncertainties of real life, general investment as compensation would lead to a high variance of the welfare of future generations. All the discussed uncertainties can affect future rates of substitution at the level of a future generation's welfare function and, hence, the welfare effects of compensatory investment. Either a high risk about the adequacy of compensation would have to be accepted, or compensating investment would have to be made well in excess of Hartwick's rule to ensure adequacy of the compensation with the desired likelihood. Since the concept of welfare is non-operational a weak sustainability constraint is non-operational under real life uncertainties. It appears impossible to determine the expected welfare of a remote generation resulting from current depletion of natural capital depletion and compensation through general investment. This weak sustainability constraint, therefore, does not satisfy the requirements of intergenerational justice under real life conditions.

The uncertainty about substitutability at the level of a future generation's welfare function can be alleviated by imposing sustainability constraints separately on consumption streams that generate welfare (level 2 in Figure 4.1). These consumption streams are the services derived from depletion of natural capital, such as heat, transportation, nutrition, and others. Hence, consumption from a non-sustainable source would only be acceptable if the consumption stream can be obtained at the same real cost in perpetuity. Hence, the stocks of groups of capital providing certain services such as energy, water, waste absorption or climatic stability, would have to be kept intact. A switch from one to another type of capital within such a group would be admissible. The consumption streams are the output of a production process that combines natural capital with other forms of capital. The nature of the required compensation would depend on the specific production function. Only specific investments that leads to sustainability of the consumption stream would be acceptable as compensation. Specific investment could, for example, increase the efficiency of natural capital use. Sustainability of consumption streams is more operational than sustainability of welfare since the production function for services is more likely to be known with some confidence than all relative prices in the future. Sustainability of consumption streams is stronger than sustainability of welfare since it requires specific rather than general compensatory investment, and the former is included in the latter. Uncertainty about adequate compensation would be reduced but not eliminated since technological changes may unexpectedly alter production functions. Therefore, sustainability of consumption streams would be the appropriate constraint if there was sufficient confidence in understanding and predicting the production function but insufficient knowledge of future relative prices.

The next stronger sustainability constraint would apply to resource supplies (level 3 in Figure 4.1). This constraint would allow the use of natural capital only if the supply streams entering production are made sustainable. This constraint would apply separately to the supply of energy, water, the atmosphere's capacity to absorb emissions etc.. This constraint applies to the inputs to production and is stronger than the one applying to consumption streams since it does not allow for substitution at the level of the production function. Sustainability of outputs can be achieved through sustainability of inputs but also through substitution between inputs. Compensation under sustainability of resource supplies would have to be made through sustainable substitutes, such as renewable energy sources for non-renewable ones. Hence, each stock of capital providing certain basic inputs to production such as energy, water, waste absorption or climatic stability, would have to remain intact, however, a switch from one to another type of capital within any such a group would be admissible. Sustainability of resource supplies further restricts the choices of earlier generations, however, it is also more operational and further reduces uncertainty about adequate compensation since the uncertainty about the production function is avoided. However, uncertainty remains about potential alternative high-value uses of individual natural resources. This sustainability constraint would be applicable if there is considerable uncertainty about technological change or the nature of the production function but sufficient confidence that no alternative high-value uses of the depleted resource will be discovered in the future.

Finally, the strongest sustainability constraint would separately require sustainability of extraction from all different types of natural capital (level 4 in Figure 4.1). Only sustainable yields of renewable resources could be harvested and no non-renewable resources could be used. The only admissible substitution would be restoration of equal natural capital at another location. This sustainability constraint would eliminate the uncertainties, except for uncertainty about stock size, harvest and sustainable yields, and would be very operational. However, it would drastically restrict choices and ignore the existence of substitutability between different resources and, to some degree, between natural resources, technology and human-made capital. Since such a strong constraint seems to exclude many activities that would unambiguously benefit all generations, it would be too strong for most instances unless there is a significant possibility for not yet known alternative high-value uses for a resource. The potential future value of genetic material and diversity would require this strongest sustainability for biodiversity which would, for example, preclude the possibility to compensate for the extinction of species.

A sustainability constraint at levels 2 or 3 involves compensation through functional substitutes that provide the same services as the resources they are compensating for. For example, different sources of end-use energy would be functional substitutes. Compensation for the depletion of non-renewable energy resources would have to be investment in sustainable energy sources rather than in energy intensive production facilities. The quantity of such compensating investment has to ensure that the total capital for provision of energy remains intact. This means, the capital stock retains the ability to generate the presently consumed amount of energy in perpetuity. By restricting compensation to functional substitutes, the problem of estimating future prices would be alleviated, since comparison can be made in physical units of energy service.

The stronger sustainability constraints reflect the intuition that future generations can be more adequately compensated through functional substitutes and provide a built-in insurance for the future costs of current economic activities. Since the prices of functional substitutes are positively correlated, the value of the compensation is high whenever the value of the depleted resource is high and vice versa. A stronger sustainability constraint, therefore, ensures adequate compensation with a higher degree of robustness. As a result, compensation through functional substitutes is a cheaper way for current generations to provide adequate compensation. The overly optimistic assumption that technological progress will always increase society's opportunities is unrealistic and should be avoided. Hence, evaluation of substitution opportunities should be based on currently available technology or foreseeable technological development. This reflects prudent behaviour in view of the experience that technology and increasing knowledge can lead to information that significantly reduces the opportunities of future generations (see Daly and Cobb 1989, p.198).

For most situations, the foregoing discussion would suggest a sustainability constraint based on groups of functionally substituting types of capital. However, the choice of a specific sustainability constraints in a particular situation involves considerable judgement and should depend on the degree of risk aversion, the nature and degree of uncertainty about the adequacy of intergenerational compensation and the availability of substitutes. The search for the appropriate sustainability constraint in a given situation involves the trade-off between the risk of inadequate compensation and expected welfare gains for all generations. The stronger the sustainability constraint, the more the choices of the current generation are constrained by it. A stronger constraint reflects a more cautious approach involving less interference with the natural support system at the cost of reduced welfare. Under complete certainty, the weakest sustainability constraint would suffice. The less knowledge is available on the nature of substitutability, the stronger the sustainability constraint should be. If no substitute is available at the level of the selected sustainability constraint, the depletion of natural capital would not be permitted. Since intergenerational compensation is a surrogate for voluntary trade between distant generations, between which direct trade is not possible, the selected sustainability constraint should leave early generations sufficiently confident that later generations would have agreed with the substitution undertaken and the compensation provided in the given situation.

3.2 The Geographic Scale of Sustainability

The chosen sustainability constraint can be implemented at various geographic scales. Non-declining capital stocks can be required on a global, national, regional or local level. For example, a carbon dioxide emission constraint could be imposed on a global scale. Alternatively such constraint could be imposed on countries separately. Even stronger, every city or every project could be required to meet a carbon dioxide emission constraint. Similar to the choice of the level of sustainability, the choice of the geographic scale depends on the trade-off between gains from substitution and the risk of inadequate compensation. Hence, the geographic scale should depends on the substitutability between natural capital at different locations. The atmosphere is a global resource, and carbon dioxide emission reductions at any place are perfect substitutes. For global public resources (atmosphere, oceans) and for tradable resources, such as oil which has a high value compared to transport costs, the sustainability constraint should be implemented on a global scale. Otherwise, the market or shadow prices of natural capital depletion would differ across countries, and the potential gain from equalizing the marginal cost of reducing natural capital depletion across countries would not be realized.

The desirable use of a sustainability constraint on a global scale for global and tradable resources is hampered by the absence of effective mechanisms for international political coordination. Therefore, in the absence of a global sustainability constraint, individual countries could impose a national or local sustainability constraint even for global and tradable forms of natural capital. In this case, compensatory investment would not be determined on the global scale but depend on every individual countries' production or consumption. While a global constraint should be the ultimate objective, international lending agencies could play an important role in supporting the application of a national sustainability constraints even for global public resources. Similarly, if there was not already a sustainability constraint implemented at the national level, it could be imposed at a local or even project level. This approach would lead to the "bottom up" implementation of sustainability without the long delays inherent in national or even global decision making.

There are examples of natural capital that cannot be easily substituted by natural capital at another location. Where natural capital is local in nature, a sustainability constraint should naturally be applied at the local level. The services rendered by a watershed are not readily tradable. Hence, such natural capital has to be maintained intact at the local level and the destruction of one watershed cannot be compensated by restoration of a watershed in another country. Also, fresh-water on one continent is not a good substitute for fresh-water on another continent. Since transportation costs are usually prohibitive, sustainable water supply should be required at the regional level.

4 Project and Policy Evaluation Under a Sustainability Constraint

This section applies the sustainability constraint suggested in the previous section to the evaluation of projects or policies which increase or decrease the depletion of natural capital. In this section, a "sustainable supply rule" for shadow pricing natural capital depletion is suggested The sustainable supply rule reflects the sustainability constraint and the requirements of evaluation under uncertainty, as well as intergenerational equity and efficiency, on which the sustainability constraint was based. There is no inherent reason why an individual project needs to be sustainable. It is perfectly acceptable to undertake a project that generates positive net benefits over the finite lifetime of a project if all costs are properly included in the analysis and if no costs are imposed on future generations. However, the shadow prices used for the depletion of natural capital should reflect the appropriate sustainability constraint in order to overcome the inherent limitations of conventional evaluation discussed at length in section 2. If a sustainability constraint was imposed and compensation was made at the national or global level, market prices for natural capital would already reflect this sustainability constraint and no further adjustments would need to be made for project evaluation. However, if a sustainability constraint is not yet implemented at a higher level (currently this is likely to be the case), shadow prices that reflect the appropriate sustainability constraint need to be calculated and used at the project level. Also, compensation needs to be made for natural capital depletion caused by the project.

4.1 The Sustainable Supply Rule

This section puts the theoretical concepts discussed so far into practice. It proposes an operational sustainable supply rule for shadow pricing natural capital depletion and determining the appropriate intergenerational compensation for depletion of natural capital. The sustainable supply rule is an application of the theoretical requirements discussed before. The sustainable supply rule combines elements of Pearce's (Barbier, Markandya and Pearce 1988, and Pearce 1990) proposal to impose a sustainability constraint on a portfolio of projects, Page's (1977) suggestion to tax resources such that their real price would remain constant over time and El Serafy's (1989) approach for adjusting national income accounts to reflect resource liquidation. Through the requirement of sustainability for groups of functional substitutes, however, the sustainable supply rule is more operational than, i.e., the Pearce approach.

The sustainable supply rule allows the depletion of natural capital only if the depleted natural capital is replaced by compensating investment that functionally substitutes for the depleted capital. Natural capital depletion would be evaluated at the sustainable price of the services derived from it. This sustainable price is the cost at which the services from the depleted natural capital can infinitely be provided through a sustainable substitute if for every unit of depleted natural capital the sustainable price is invested in production of the substitute. If a functional substitute for the depleted natural capital is not available and there is considerable uncertainty about its future value, natural capital of the same type needs to be restored or depletion of natural capital would not be allowed (the shadow price would be infinite). If there is sufficient confidence that the future value of natural capital can be estimated, depletion would be acceptable if compensation is made for future generations sufficient to offset the foregone benefits they could have derived from natural capital.

The sustainable supply rule is applicable for a sustainability constraint at any geographic scale. At the level of national policy making, the rule could be used to determine an adequate resource depletion tax. Whenever the sustainable supply rule is not applicable in a given situation, the appropriate alternative approach for evaluation should be derived from the three theoretical requirements derived for adequate evaluation. In the following discussion, the derivation of the sustainable supply rule is explained for the simplest possible case geared toward application at the project level: the depletion of a non-renewable resource that has a perfect sustainable substitute. Following El Serafy's (1989) approach, the benefits from depletion of natural capital need to be divided into an income and a compensation component. The compensation component would be allocated as a cost to resource depletion. It would be determined such that when the compensation component is invested in production of a sustainable substitute for the non-renewable resource, it would, after exhaustion of the non-renewable resource, lead to an infinite benefit stream from consumption of the sustainable substitute equal to the income component. Benefits from the non-renewable resource would be shared with all following generations through the constant income component which is generated through compensatory investment.

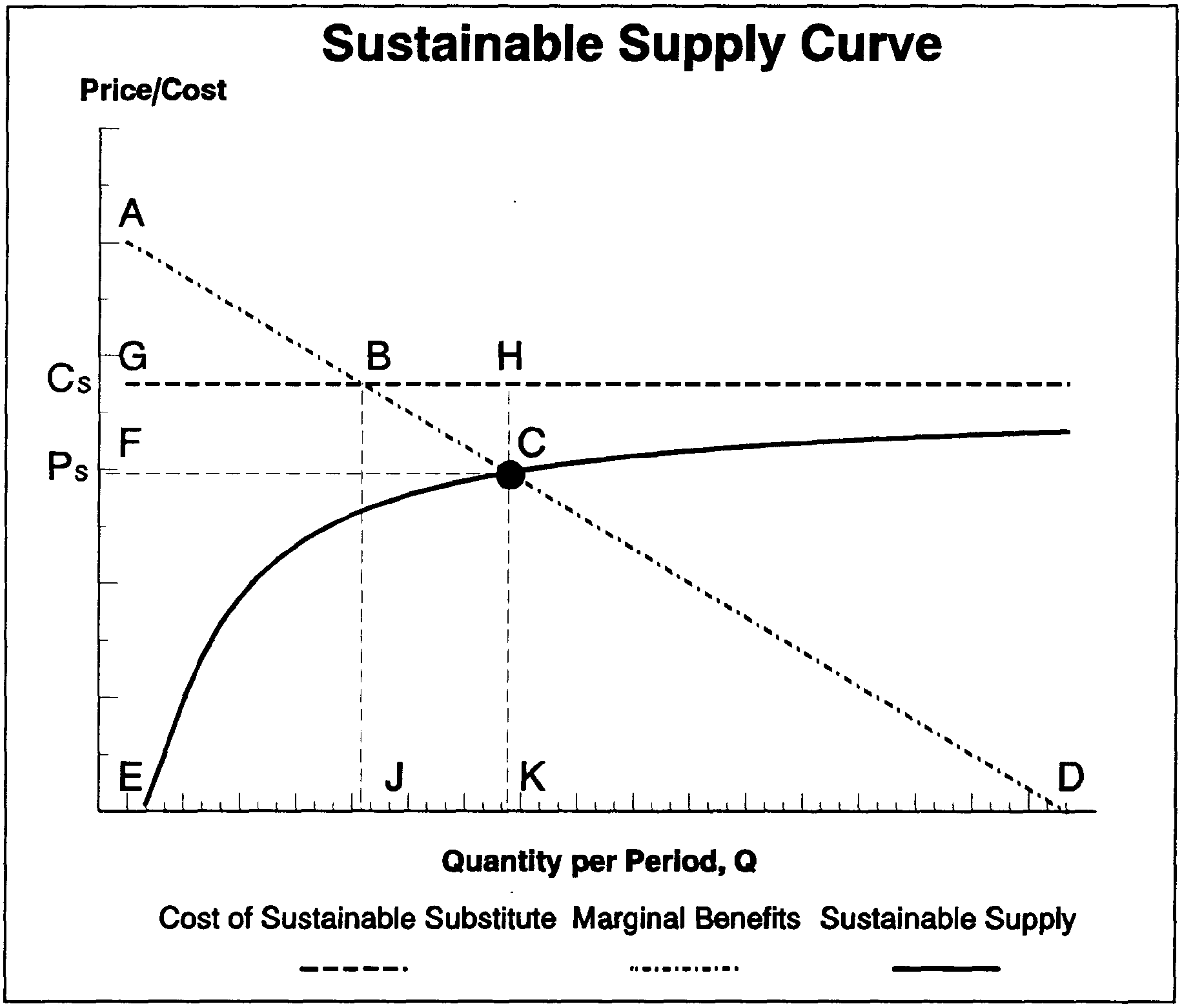

Figure 4.2 The Sustainable Supply Curve

The demand curve for a service that can be provided by a non-renewable resource or its sustainable substitute is shown in Figure 4.2. For simplicity, it is assumed that the non-renewable resource can be extracted at zero cost. The current unit cost of producing the sustainable substitute is assumed to be C_s. This is shown through the horizontal supply curve at C_s. The line ABCD represents the demand (or marginal benefit) curve. At the price P_s, no sustainable substitutes would be offered and demand would have to be satisfied with the non-renewable resource. Market demand at price P_s would equal the distance EK and total benefits from consumption of the resource would be the area under the demand curve up to the quantity used, ACKE. This rent consists of two components: the owner of the resource would receive revenues equalling FCKE; the consumers would receive the (non-monetary) consumer surplus ACF. The sustainable supply rule requires that the revenues FCKE be the compensation component to be invested and the consumer rent ACF be the income component accruing to the present generation for consumption. The point C on the demand curve is determined such that the income component can be sustained for all generations.

Compensating investment into the sustainable substitute would, in time, reduce the unit cost of the sustainable substitute from its current level C_s. This cost reduction occurs because compensating investment into improvements of technology actually reduces production costs or because compensating investment is used as a free addition to the capital stock for production of the substitute. Now, the sustainable price, P_s, which also defines point C on the demand curve, is determined such that the cost of producing the sustainable substitute is reduced to P_s exactly at the time when the non-renewable resource is depleted. At that time, production of the sustainable substitute will begin. Hence, this procedure ensures that a sustainable price is chosen at which the same quantity of the service from the resource will be provided in perpetuity; first from the non-renewable resource and later from the sustainable substitute. The term sustainable price refers to the fact that this price does not change with depletion of the non-renewable resource.

In the simplest case, the non-renewable resource is homogenous with zero extraction costs and supply of the sustainable substitute is infinitely elastic at C_s. For the quantity of the resource extracted per period, Q, the sustainable price, P_s, would have to be set such that $P_s \cdot Q$ (the area FCKE in Figure 4.2) invested in every period until depletion of the non-renewable resource, would generate a return of $(C_s - P_s) \cdot Q$ (area GHCF) in every period after depletion. Here, r is the (continuous time) rate of return on investment in sustainable substitutes, S is the total stock of the non-renewable resource and S/Q is, therefore, the lifetime of the resource. The return to the compensating investment reduces the cost of the sustainable substitute which, in turn, leads to a constant sustainable price. The quantity Q of the resource will be available at the price P_s, before depletion from the non-renewable resource and thereafter from the sustainable substitute.

The compensation component invested throughout the lifetime of the non-renewable resource must be sufficient to yield an infinite subsidy stream that reduces the cost of the sustainable substitute to the sustainable price for an equal consumption quantity per period. This is the case if the present value of the finite stream of the compensation component equals the infinite stream of the subsidy after resource exhaustion which occurs after S/Q periods. The present value of the compensation component, K, from time 0 to S/Q is:

$$K = \int_0^{\frac{S}{Q}} e^{-rt}\, Q \cdot P_s \, dt \;=\; \frac{Q \cdot P_s}{r} \left(1 - e^{-r\frac{S}{Q}}\right) \tag{1}$$

The present value of the subsidy stream, T, from time S/Q until infinity is:

$$T = \int_{\frac{S}{Q}}^{\infty} e^{-rt}\, Q(C_s - P_s) \;=\; e^{-r\frac{S}{Q}}\, \frac{Q(C_s - P_s)}{r} \tag{2}$$

equating T and K and dividing both sides by Q/r:

$$P_s \left(1 - e^{-r\frac{S}{Q}}\right) = e^{-r\frac{S}{Q}}\, C_s - P_s \tag{3}$$

Solved for P_s, this results in the following equation for the sustainable price:

$$P_s = e^{-r\frac{S}{Q}}\, C_s \tag{4}$$

Equation (4) is based on highly simplistic assumptions and not directly applicable in most instances. However, the assumptions of zero extraction costs for the non-renewable resource and perfectly elastic supply of the sustainable substitute can be relaxed at the cost of complicating equation (4). If there is a constant extraction cost, E, per unit of the non-renewable resource, the compensation component would be:

$$K = \frac{Q(P_s - E)}{r}\left(1 - e^{-r\frac{S}{Q}}\right) \tag{5}$$

Similarly, P_s is calculated by equating K and T, and solving for P_s:

$$P_s = E + e^{-r\frac{S}{Q}}\,(C_s - E) \tag{6}$$

where P_s is total price including extraction cost. The appropriate user cost is P_s-E. Similar equations for sustainable supply can be calculated for rising extraction costs or a situation in which a stock of compensating investment already exists. Also, a similar expression can be found if no perfect sustainable substitute exists. If the service which is to be supplied sustainably is produced from natural capital and another reproducible input, the expression for the sustainable price can be derived from the production function by optimizing the inputs over time such that a constant stream of the service is obtained at least cost.

If the extraction rate of the non-renewable resource, Q, was increased, the compensation component would have to increase as well, since the reduced lifetime of the resource would leave less time for returns of the compensating investment to compound. The sustainable price would, therefore, be higher if the resource depletion rate was higher and vice versa. Hence, equation (4) describes a positive functional relation between quantity of the service from the resource consumed per period and the sustainable price. The typical shape of the resulting sustainable supply curve is shown in Figure 4.2. The term sustainable supply curve reflects the steady nature of this supply curve as opposed to an imaginary supply curve with Hotelling-depletion which would shift upward to reflect opportunity costs which would be rising with the scarcity of the non-renewable resource. The sustainable price can be read from this curve with knowledge of annual depletion of the resource. If the resource was supplied according to the sustainable supply curve, point C would be the market equilibrium. The sustainable price would be the shadow price to be used for the valuation of depletion in a resource extraction project or for the valuation of the output from a project producing a substitute for the resource. Under this rule, actual investment of the compensation component (sustainable price times quantity of the resource depleted) would be required for the project to be acceptable.

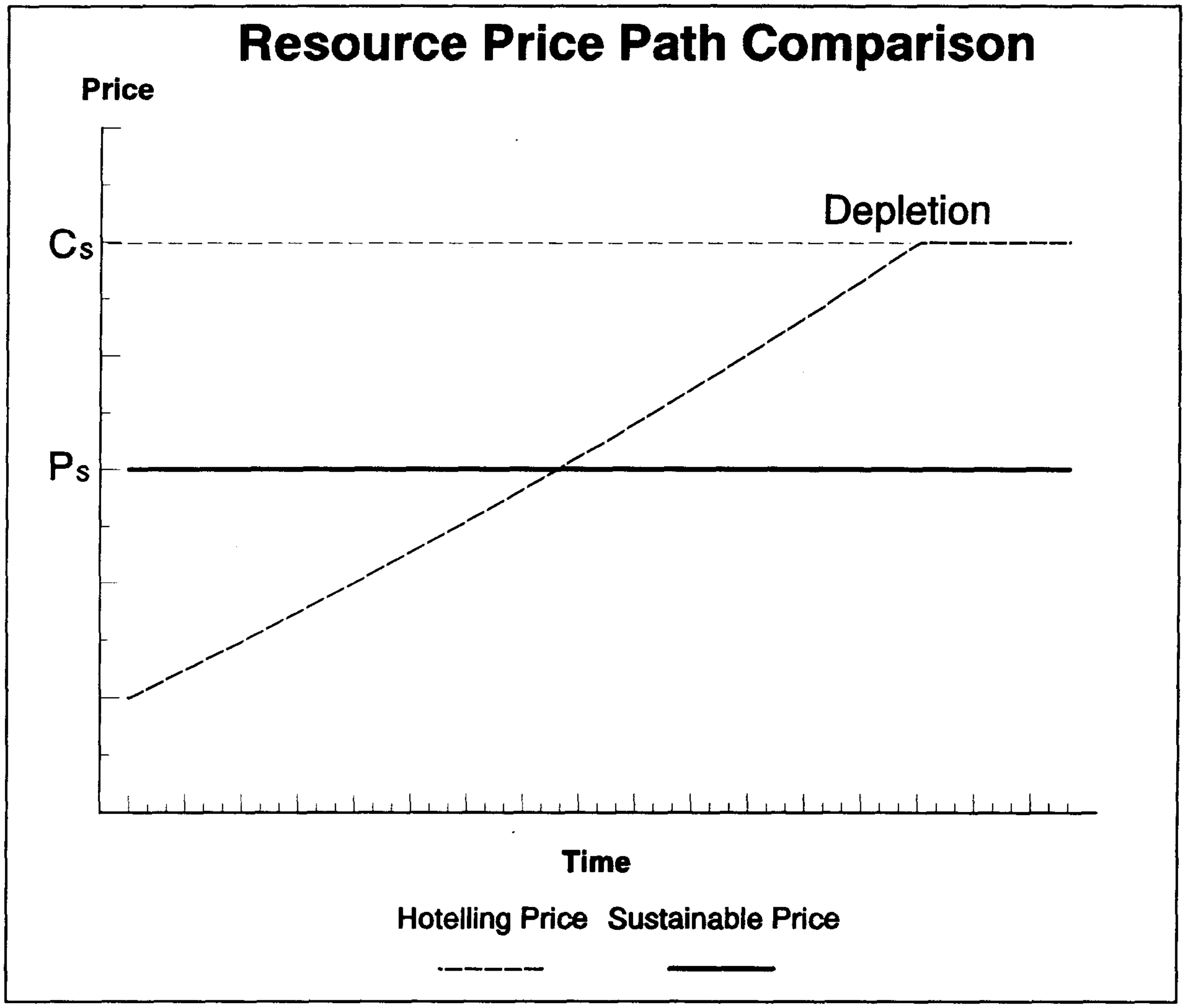

Figure 4.3 Resource Price Path Comparison

Figure 4.3 compares the price paths resulting from use of the sustainable supply rule and conventional depletion according to the Hotelling rule. With depletion according to the sustainable supply rule, the price would remain constant at level P_s with depletion occurring somewhere along the horizontal line. Optimal depletion in perfect markets without a sustainability constraint would follow the Hotelling rule. C_s would be the cost of a back-stop technology. Therefore, the price of the resource would rise at the rate of interest with the initial price set such that depletion occurs exactly when the price reaches C_s as shown in Figure 4.3. In the initial years, a larger amount of the resource would be available at a price lower compared to the sustainable supply rule. In later years, a lesser quantity would be available at a higher price. With conventional depletion, the total rent accruing in the early years would be close to the area ADE in Figure 4.2. This rent would fall gradually to ABJE in the last period before depletion. For all periods after depletion, total rent would be only ABG. With the sustainable supply rule, rents would be ACF in all periods. The timing of resource exhaustion under the different regimes would depend on the relation between discount rate and the rate of return on the specific compensating investment.

Use of the sustainable supply rule is clearly preferable to the use of the currently most applied rule, "ignore the costs of natural capital depletion". However, the justification of the sustainable supply rule does not lie in formal social welfare maximization and it may be possible to show that the sustainable supply rule is inferior to a conventional efficiency approach (the Hotelling price path) IF the conditions for first-best decision making are met. These conditions would include certainty or alternatively complete forward markets, internalization of all external costs, profit/social-welfare maximizing decision makers and the existence of effective wealth transfer mechanisms between generations. The defense of the sustainable supply rule rests primarily on the assessment that these assumptions are highly unrealistic. In particular, there are no explicit institutional arrangements in existence that would guarantee the desired level of welfare for future generations. The conventional approach (depletion according to the Hotelling path) would be preferable only if there was a situation where market failures and systematic biases were removed, uncertainty about substitutability and inter-dependencies in complex natural systems was sufficiently resolved, and intergenerational welfare transfer mechanisms were in place.

4.2 Application of the Sustainable Supply Rule

In this subsection, practical applications of the sustainable supply rule will be discussed and illustrated by means of several examples. First, applications to non-renewable and renewable natural resources, land use, and emissions will be discussed. Then, complications arising from unsustainable use of project outputs, international trade, and different types of compensating investment will be assessed.

The common practice of ignoring the user cost in evaluating natural resource extraction projects is clearly unacceptable. The sustainable supply rule would be used to calculate the appropriate depletion premium under a sustainability constraint. Consider the example of an agricultural project based on ground-water depletion. A sustainable supply curve for water can be found by estimating the cost of compensating investment in sustainable water supply, for example a solar-energy powered water desalination plant. Using the present unit cost of producing desalinized seawater, C_s, the sustainable price for ground-water, P_s, would have to be determined such that if an amount equal to P_s times the depletion rate was invested in desalination technology, then this investment would be able to provide desalinized seawater of the same quantity at the cost P_s for every year after depletion of ground water. The sustainable price of ground water would be calculated by using equation (4) with the current depletion rate Q, total stock left in the ground, S, and rate of return on compensating investment, r. To evaluate a project that uses ground water, the sustainable price of water, P_s, would be subtracted from project benefits as a unit cost for ground-water depletion.

For shadow pricing the depletion of a non-renewable energy resource, such as oil, C_s would be the cost of producing a sustainable substitute, such as a unit of solar energy. Compensating investment might be most profitable in research and development in order to increase the efficiency of photovoltaic energy generation. The size of the required compensation component would be determined such that solar energy would become available at the sustainable price of one energy unit from oil in the same quantities after depletion of the oil. Today, oil depletion would be evaluated at the sustainable price. The royalty or extraction tax levied from extracting companies should be set according to equation (6) for the sustainable price with non-zero extraction costs. Alternatively, compensating investment could be made in technologies to increase energy use efficiency. An increase in energy use efficiency would decrease the cost of sustainable energy supply in the future accordingly and, thereby, lead to a lower sustainable price of energy service from non-renewable resources.

The sustainable supply rule can be applied to renewable resources as well. If a renewable resource is harvested sustainably, no special problems arise since depletion of natural capital does not occur. Therefore, the appropriate price is the marginal social benefit of the resource at the level of the sustainable yield. For the depletion of a renewable resource, the sustainable supply rule can be applied in analogy to non-renewable resources. Compensatory investment for depletion has to ensure that the same quantity can be extracted infinitely at the same price. It would be difficult to imagine a functional substitute for forests. Therefore, compensating investment for harvesting a forest above its sustainable yield would be investment into enlarging the forest area such that the harvested amount would become the sustainable yield of the enlarged forest area. For example, if a forest is harvested at a rate x, leading to depletion after y years, then compensation would take the form of acquiring additional land and investing in reforestation such that this new forest has a sustainable yield of x after y years. The sustainable price of forest depletion would have to cover the costs of expanding the forest area accordingly.

The common assumption of a zero opportunity cost of land would, in most instances, be unacceptable under a sustainability constraint. The lack of observable commercial uses would be insufficient for the assumption of zero opportunity cost of land, especially if a project does not only use but also degrade the land While the ecological value of wildlands would differ considerably, assigning a value of zero would be justified only in extreme circumstances such as sustainable use of desert lands. In all other instances, a default value above zero would be appropriate. To determine the land value in the absence of apparent commercial uses or a reliable market price, the replacement cost should be considered. This would be the cost of rehabilitating or restoring similar lands that are already degraded. If a project takes land out of the existing stock of productive land or wilderness areas, it should carry the cost of maintaining the stock intact by rehabilitating or restoring a degraded area of equal size. For example, a mining project would have to carry the cost of land rehabilitation not at the time of mine closing but at the time of mine opening. Due to the effect of discounting, this change would significantly increase economic rehabilitation costs.

The common practice of ignoring the costs of uncertain damage resulting from emissions is equally unacceptable under a sustainability constraint. The expected damage costs for most pollutants would be strictly greater than zero and an explicit evaluation of expected damages is preferable even under significant uncertainty. In the absence of any knowledge about the damage costs, the costs of a sustainable substitute (the cost of complete pollution abatement or the cost of compensatory reduction of equivalent emissions elsewhere) should be used as default value for the unknown damage costs. This default value is reduced if it can be shown that damage costs are less in a specific instance.

There are no functional substitutes available for the services provided by the atmosphere. The composition of the atmosphere constitutes natural capital which is depleted by increasing the carbon dioxide concentration. Since, there is no known substitute for the atmosphere in its natural composition, compensatory investment would have to maintain this type of natural capital intact. Hence, a new project that would increase the atmospheric carbon dioxide concentration would have to bear the costs of investment, for example in reforestation, that would absorb the same amount of carbon dioxide that is discharged by the initial project. Alternatively, investment could be undertaken in increased energy efficiency that would lead to the same offsetting effect on net carbon emissions. The compensating investment has to be undertaken and the costs are allocated to the initial project. The initial project should only be undertaken if it yields a positive return after subtraction of the cost of the compensating investment.

So far, resource depletion, land use and emissions resulting directly from the project were considered. Some projects produce output that is put to unsustainable use. If the market price of the output does not reflect a sustainability constraint on that output's use, output prices need to be adjusted. For example, even if the coal reserves of the earth were considered infinite and there was no depletion premium associated with a coal mining project, the current use of coal is unsustainable due to the carbon dioxide emissions resulting from coal combustion that contribute to the greenhouse effect. Unless a sustainability constraint is already imposed on the use of coal, and this is reflected in the market price, the output price used in evaluating the mining project needs to be adjusted for unsustainable use even though the carbon dioxide emissions are occurring outside of the project.

Environmental problems such as carbon dioxide emissions, loss of biodiversity and deforestation reach beyond country borders. Even national environmental degradation may lead to international externalities through resulting migration and political tension. However, project evaluation is usually done from a national point of view, maximizing net social benefits accruing in one individual country. In the presence of international externalities, national welfare maximization leads to inefficiencies. Since several environmental issues can only be dealt with at a global scale, analysis under a sustainability constraint must take a global perspective. This means that even international prices need to be adjusted if they do not reflect the appropriate sustainability constraint. Hence, even if coal is exported, the output price needs to be adjusted for the cost of unsustainable coal use resulting in carbon dioxide emissions. This global view may counter the individual interests of the national government that is implementing the project. Therefore, transfer payments between nations would likely be required to achieve sustainability for traded resources and international externalities. Concessionary lending through institutions, such as the Global Environment Facility, administered jointly by the World Bank, UNDP, and UNEP, would be appropriate to facilitate the required transfer payments.

Finally, the nature of compensating investment and the calculation of the returns on such investment requires further discussion. In principle, any form of compensating investment is acceptable if it leads to provision of a sustainable supply of the substitute at the sustainable price. The simple case, for which equation (4) was derived, refers to a situation in which facilities for the sustainable production of the substitute already exist. Then, compensating investment does not need to provide the sustainable substitute itself. In cases where technological improvement in the existing sustainable substitute is unlikely, compensating investment should be made in the form of general sustainable investment in the economy. Proceeds of this investment would then be used to subsidize the production of the sustainable substitute in the existing facilities after the non-renewable resource is depleted. In the more likely case that production facilities for sustainable substitutes do not yet exist, compensating investment would be made in such production facilities for a sustainable substitute. Only after such investment is sufficient to produce the required quantity of the substitute, further investments should be made into general sustainable production to subsidize the cost of the sustainable substitute. In either case, r, would be the real rate of return on the actual compensating investment undertaken.

In many cases, the most effective investment for the reduction of the cost of a sustainable substitute would be into research and development (R&D). While the return on R&D is difficult to estimate, the problem is alleviated in this case since the relevant rate r is the rate of return on R&D measured at the fixed output price C_s. Therefore, uncertainty prevails only about the success of the R&D program in physical and not in economic terms. Measurement of return on R&D in terms of output price C_s explains why through such compensating investment worthwhile R&D into sustainable substitutes might be undertaken that would not be undertaken under a pure market arrangement. Due to the public good nature of information and knowledge, there are many reasons to believe that market forces alone will not bring about the efficient level of R&D activities. Since patent protection is rarely complete, private investors could normally not reap the full return on their R&D expenditures. Competitors would imitate the innovation or circumvent the patent which, in turn, would lead to a drop of output prices below C_s (see Tirole 1988, pp. 389-419, chapter 10).

Use of the sustainable supply rule may lead to the rejection of projects that deplete natural capital and that were considered desirable without a sustainability constraint. However, other projects are restoring natural capital and would be more desirable under a sustainability constraint. Imagine a country that uses forests or ground water resources unsustainably. A proposed conservation project that would increase water use efficiency or restore forests, would under conventional analysis be evaluated by comparing a with-project scenario and a without-project scenario. To justify the project, the pervasive benefits from reforestation would have to be enumerated and evaluated. Because of the pervasive nature of benefits generated by natural capital, this would lead to a systematic underestimation of the economic benefits from the project. Under a sustainability constraint, the default assumption would be reversed and the appropriate comparison would be between a with-project scenario and a scenario with the next best project that would achieve sustainability. A reforestation project would be compared with a project that provides a sustainable substitute for fuelwood, such as energy use efficiency increases or a solar energy project, and should be implemented if it was the least cost alternative for achieving sustainability. This approach would be reflective of the view that the analysis of an individual project does not need to confirm that sustainability is desirable. Rather, the analysis should ensure that the least-cost option for achieving sustainability is pursued.

5 A Stylized Case Study: An Oil Development Project

The stylized case study in this section is presented to illustrate the application of the sustainable supply rule with a real life example. This presentation is based on case studies of several World Bank projects (von Amsberg 1993). However, many simplifying assumptions have been introduced in order to focus attention on methodology rather than on technical details of the underlying project. The case study shows that reasonable shadow prices can be calculated with very moderate effort. While care has been taken to use reasonable cost estimates and make reasonable assumptions, there is certainly ample room for improving the estimates and calculations. The basic information underlying the case study, such as prices, exchange rates and cost estimates, is based on the Staff Appraisal

Report of the project. The analyzed project consists of the commercial development of an off-shore oil field that is jointly owned by the national petroleum company and the domestic subsidiary of a multinational corporation. The recoverable reserves of the oil field are estimated at 330 million barrels and would be extracted over the 21-year lifetime of the project. Peak production will be reached in year two with production declining after year four. The project was appraised by the World Bank with an economic rate of return of 51%. This analysis did not include a user cost or depletion premium for the extracted oil. Hence, the economic rate of return reflects the full resource rent without considering the opportunity costs of depletion. The price projections for oil that were used for the calculation of the economic rate of return are flat for the lifetime of the project (around $22/bbl in constant 1990-$).

5.1 The Issues

Two main issues arise with respect to the sustainability of hydrocarbon extraction and its evaluation. First, the extraction of a non-renewable resource is unsustainable due to the limited reserves. Second, the use of hydrocarbons as energy source is unsustainable since, at current consumption levels, its combustion leads to accumulation of carbon dioxide in the atmosphere. Hence, a sustainability constraint needs to reflect these two types of natural capital depletion.

Oil from other oil fields in the country is obviously an almost perfect substitute for oil from this project. Since oil is primarily used as an energy commodity, substitution of oil with another storable form of energy would also be acceptable under a sustainability constraint. Other hydrocarbons, such as gas, evaluated at their energy content, would be almost perfect substitutes for oil. However, these substitutes are finite as well. They can stretch the lifetime of the non-renewable resource but they cannot substitute for it in perpetuity. Beyond that, compensation would have to be based on truly renewable energy sources.

Substitution would also be acceptable at the level of production of energy services from primary energy and capital. Within limits, capital can substitute for primary energy through increased efficiency in energy use. First, at any given level of technological development, there is some substitutability between capital and energy, i.e. through increased insulation against heat loss. Second, investments in research and development can lead to technological progress that would allow production of more energy service from the same amount of capital and primary energy. Clearly, there are limits to the substitution of energy posed by thermodynamic constraints. Lighting a room requires some minimum amount of energy regardless of the efficiency of the bulb; transport requires some minimum amount of energy regardless of the efficiency of the vehicle. However, in many instances, physical limits have not yet been exploited, leaving room for significant further substitution. The estimation of substitution between capital and energy poses problems because of the many different uses energy is put to and the difficulties inherent in anticipating technological progress. However, reasonable estimates are available that can serve as the basis for sensitivity analysis.

It is assumed that compensatory investment for current depletion would have to provide not only for a constant consumption stream but for an increasing consumption stream at a constant price. Since the size of future populations is, at least partially, dependent on decisions made at present, it is reasonable to assume that the current generation should bear at least some responsibility for satisfying the demands of an increasing human population. Also, taking the large disparities in energy consumption between countries into account, it can be argued that rich nations whose consumption accounts for the largest share of unsustainable energy resource depletion, should pay a price for depletion that provides the opportunity for poorer nations to increase their energy consumption at the same low cost currently enjoyed by the high-energy consuming countries.

The use of hydrocarbons leads to the release of carbon dioxide that contributes to the greenhouse effect which is expected to lead to global warming. While the precise impacts of an increasing carbon dioxide concentration in the atmosphere on climate are still controversial, it is now well established that burning of fossil fuels has already led to an increase in the atmospheric carbon dioxide concentration. Annual carbon dioxide releases are currently estimated at 5.6 billion tons of carbon from fossil fuels and 0.6 billion tons from changes in land use (data from Deutscher Bundestag 1989). It is estimated that 3 to 4 billion tons of carbon accumulate in the atmosphere every year. Hence, carbon dioxide releases would have to be roughly cut in half to avoid further accumulation of carbon dioxide in the atmosphere. Even if a drastic reduction in carbon emissions is unrealistic in the short term, carbon releases would have to be reduced to the absorption capacity of the atmosphere, estimated at 2 to 3 billion tons of carbon per year, in the long-term.

In summary, a sustainability constraint would be imposed on supply of the economy with energy services, under acceptable levels of carbon dioxide emissions. The sustainable price for the depletion of oil should take into account substitution possibilities between different fossil fuels and between non-renewable and renewable energy sources. It should also reflect possible increases in energy use efficiency and long-term limits on acceptable carbon dioxide emissions. It should be based on a sustainable price for the country's oil and gas reserves; it should take the expected growth in energy demand into account; it should incorporate expected efficiency gains in energy use; and it should consider restrictions on acceptable carbon dioxide emissions.

5.2 Assumptions

Extraction costs. The extraction costs for oil from this field are $4.4 per barrel ($2.4/bbl development costs and $2/bbl recurrent costs).

Oil reserves. The country has many other, yet undeveloped, oil reserves. Since other oil reserves are perfect substitutes for the oil field to be depleted, those other oil reserves can be depleted before energy supply has to be converted to solar hydrogen as the sustainable substitute. The oil reserves are estimated at about 22 billion barrels. At the current extraction rate of 1.6 million barrels per day or 584 million barrels per year, these reserves would last 37.7 years. Extraction costs are assumed to be constant at $4.4/bbl.

Gas reserves. The country also has significant gas reserves, estimated at 150 trillion cubic feet (including undiscovered reserves). The gas reserves contain the energy equivalent of 27 billion barrels of oil (1.1 MJ per cubic feet of natural gas). Since gas can be considered an almost perfect substitute for oil, a uniform sustainable price should be calculated for all gas and oil reserves instead of different sustainability premia for different deposits. Using the total oil and gas reserves equivalent to 49 billion barrels of oil and current extraction of oil and gas equivalent to 612 million barrels per year, the lifetime of oil and gas reserves together would be 80 years. Hence, renewable energy would not need to be produced until the year 81. Extraction costs for gas are assumed to equal those of oil.

Consumption. In order to abstract from the complications of international trade, it is assumed that all gas and oil is consumed domestically. Since this assumption is obviously wrong, the impact of considering oil exports are discussed at the end of this section. Demand for energy services is expected to rise significantly over the next decades (see World Bank 1992). Both population growth and increasing per capita energy consumption would contribute to this increase that is assumed to be 3.7% per annum.

The sustainable substitute. There are several renewable energy sources that are good functional substitutes for oil. In this case study, hydrogen produced from solar energy is used as a representative renewable energy source. Hydrogen can be used in much the same way as natural gas. It can be stored and moved in tankers or through pipelines. Hydrogen can be produced sustainably by electrolysis from water and photovoltaic electricity. Hence, the energy source of solar hydrogen would be sustainable. The use of solar hydrogen is sustainable since the combustion of hydrogen releases only water and does not contribute to the build-up of carbon dioxide in the atmosphere. Solar hydrogen is used as a representative sustainable energy source because, in the long-run, it has the potential to become the least-cost substitute for hydrocarbons in many of their uses, and a variety of cost estimates are available. Also, production of solar hydrogen seems to be feasible in this specific country which has large semi-desert areas with low agricultural productivity and high solar insolation. In reality, however, solar hydrogen is likely to be only one of many renewable energy sources that would be one part of a sustainable future energy supply system.

The future cost of producing solar hydrogen is estimated at $15 per GJ (see Ogden and Williams 1989, p.39). The cost of producing solar hydrogen equivalent in energy content to one barrel of oil is $90 (with 6 GJ per barrel of oil). While others estimate the prospective costs of hydrogen higher, "overall, long-term cost assumptions in the range $70-100/BOE [barrel of oil equivalent] for the backstop technologies in markets hitherto served by non-electric fuels seem justified" (Anderson and Bird 1992, p.16).

Efficiency increases. Expected increases in energy use efficiency mean that even though the demand for energy services is assumed to rise at 3.8% per annum, primary energy extraction would not need to rise at the same rate. Substitution of capital for primary energy and investment in research and development can also satisfy part of the increasing demand for energy services. The assumptions about the costs of increasing energy use efficiency are derived from Lovins' (1990) preliminary estimates of the full technical potential for energy savings. These cost estimates are based on already available technologies. Figure 4.4 shows the cost curve, fitted to Lovins' data. The costs (in $ per barrel of oil saved) express the present value of the capital investment required to save the specified share of current primary energy input for the production of one unit of energy service. The estimated cost curve is

$$K = -3 - 10.4\,Log\left[\frac{0.85-S}{0.85}\right] \qquad (7)$$

where K is the capital cost in $ per barrel of oil saved, and S is the share of energy saved.

The assumption about the introduction of energy saving technologies are based on estimates that annual increases in energy efficiency of 2% are possible over several decades

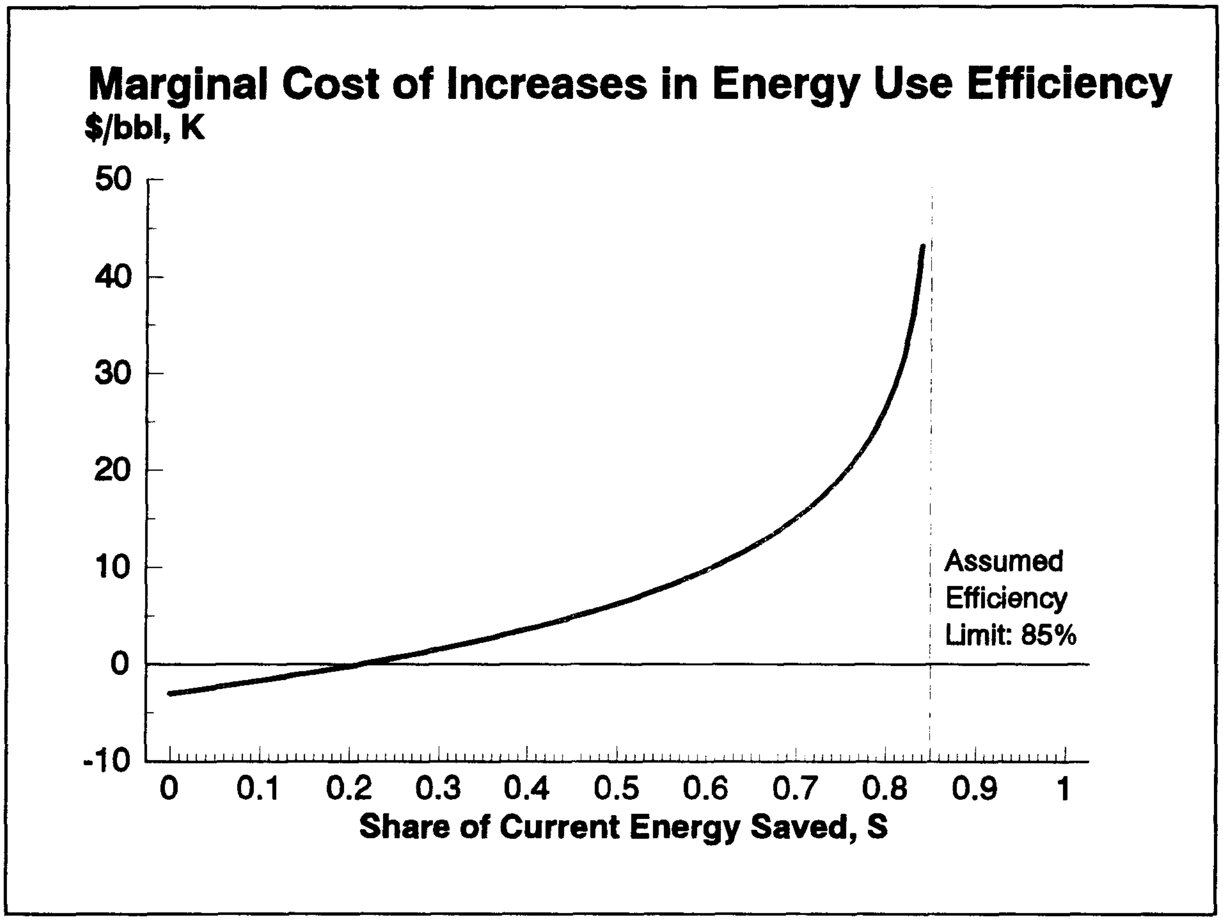

Figure 4.4 Costs of Increasing Energy Efficiency

(Worldwatch Institute 1988, pp. 41-61, chapter 3). This estimate is based on average energy efficiency increases of 1.7% per annum during the 1973-83 period and the potential to increase these achievements through increased investment.

Hence, for the following calculations it is assumed that the annual 3.7% increase in demand for energy services is accommodated by 2% efficiency increase and 1.7% increase in primary energy production per year. This is consistent with a doubling of primary energy consumption within the next forty years. With an increase in extraction of 1.7% per annum, the country's gas and oil reserves would be depleted after 50.7 years. It is assumed that efficiency increases can be obtained until the time of depletion. Also, demand is assumed to level off after year 51.

The cost for increased energy efficiency per unit of energy service, c_t, is the integral of the cost function depicted in Figure 4.4 from zero to the achieved level of energy savings, which, as discussed above, is assumed to be a function of time:

$$c_t = -\int_0^{1-e^{-0.02t}} 3 + 10.4Log\left[\frac{0.85-S}{0.85}\right]dS = \qquad (8)$$

$$7.4 + 7.4e^{-0.02t} + (10.4e^{-0.02t} - 1.6)Log[-0.2 + 1.2e^{-0.02t}]$$

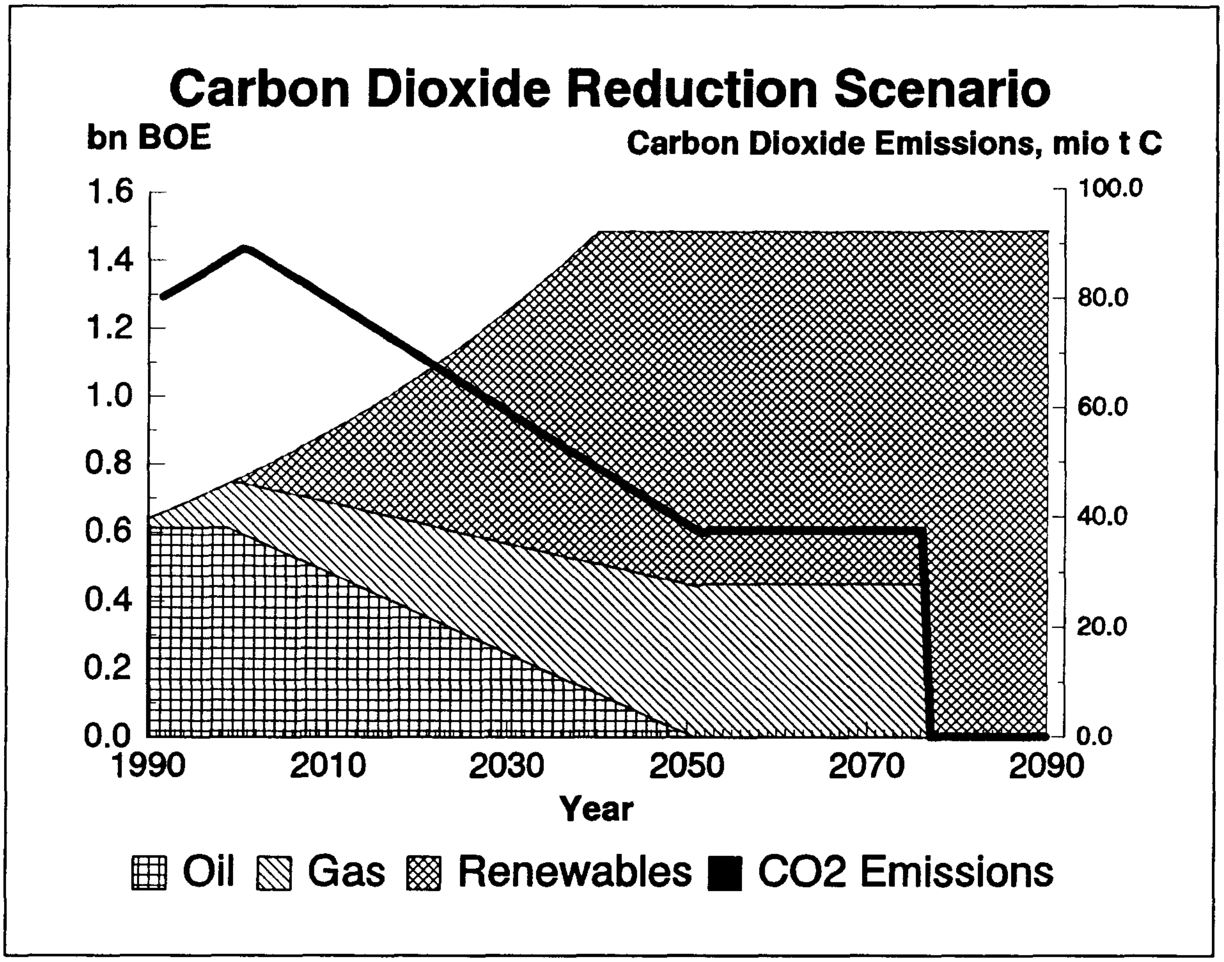

Figure 4.5 The Carbon Dioxide Reduction Scenario

Year	Total	Oil	Gas	Renew	CO_2 Emiss
	in mio bbl oil equivalent				mio t C
1989	640	612	28	0	83
1990	651	612	39	0	84
1991	662	612	50	0	85
1992	673	612	61	0	86
1993	685	612	73	0	87
1994	696	612	84	0	88
1995	708	612	96	0	89
1996	720	612	108	0	90
1997	732	612	120	0	91
1998	745	612	133	0	92
1999	758	612	146	0	93
2000	770	600	151	19	92
2005	838	541	181	116	87
2010	912	482	210	220	82
2015	992	423	239	329	76
2020	1079	364	269	446	71
2025	1174	305	298	571	66
2030	1277	246	327	704	61
2035	1390	187	357	846	55
2040	1487	129	386	972	50
2045	1487	70	415	1002	45
2050	1487	11	445	1031	40
2055	1487	0	450	1037	39
2060	1487	0	450	1037	39
tons of C per BOE:		0.1316	0.0863	0	

Carbon emissions are calculated from Deutscher Bundestag (1989), p.489: 0.29 kg CO_2 per Kwh from oil; 0.19 kg CO_2 per Kwh from gas; mass of CO_2 is 3.67 times the mass of C.

Table 4.1 Carbon Dioxide Reduction Scenario

Carbon dioxide emission constraint. In order to meet carbon dioxide emission reduction targets, an alternative scenario is developed under which extraction of the country's oil and gas reserves is constrained by the requirement that carbon dioxide emissions from all energy sources are gradually reduced to one half of 1990 levels from 2000 to 2050. This reflects an ambitious schedule for the reduction of carbon dioxide emissions, however, it follows from the requirement to reduce emissions to the estimated absorption capacity. Under this scenario, shown in Figure 4.5, oil would be depleted until 2050. The carbon dioxide emissions of gas are only 65% of the emissions of oil, compared on an energy content basis. Hence, gas extraction would be increased to the level at which total emissions from gas equal 50% of total current carbon dioxide emissions from gas and oil. All remaining energy demand (as above rising at 1.7% per annum until year 50) would have to be met with solar hydrogen. Hence, the annual extraction of gas would be constrained by the admissible emissions of carbon dioxide rather than depletion of the resource. Production of the different fuels and aggregate carbon dioxide emissions are shown in Table 4.1 and Figure 4.5. Under this scenario, gas would be depleted after 85.7 years. Thereafter, it would be fully replaced by hydrogen.

Discount rate. The sustainable prices derived in this case study are sensitive to the assumed rate of return on compensatory investment. The appropriate rate is the expected real rate of return on actual compensatory investment. The opportunity cost of capital used in the economic evaluation of most projects is between 10 and 12%. However, considering a long-term real rate of return on international capital markets in the range of 3 to 5%, it is unlikely that a real rate of return of 10 to 12% can be realized on long-term investments of very significant amounts. Furthermore, as the worldwide integration of national financial markets progresses, it would be expected that the rate of return on investment would converge to the rates obtained on international markets. Hence, a discount rate of 7% has been assumed for the calculation of a sustainability premium, with additional sensitivity analysis for a discount rate of 5%.

5.3 Project Evaluation

In order to separate the effects of the resource depletion constraint from the carbon dioxide emission constraint, sustainable prices are calculated for these two constraints separately. First, consider the resource depletion constraint. Under the imposed sustainability constraint, the price of energy service, not necessarily the price of primary energy, must be sustainable. The sustainable price of energy service is obtained by equating the present value of the cost of extraction (extraction rising at 1.7% per annum), C_X, the cost of providing solar hydrogen after depletion, C_H, and the assumed expenditures necessary to achieve the 2% efficiency increases, C_E, with the present value of revenues, R, received for energy services (rising at 3.7% per annum) provided at the sustainable price:

$$
\begin{aligned}
R &= \int_{0}^{50.7} e^{(0.036-r)t} 612 \cdot 10^{6} P_s dt + \int_{50.7}^{\infty} e^{0.036 \cdot 50.7 - rt} 612 \cdot 10^{6} P_s dt \\
C_X &= \int_{0}^{50.7} e^{(0.017-r)t} 612 \cdot 10^{6} \cdot 4.4 dt \\
C_H &= \int_{50.7}^{\infty} e^{0.017 \cdot 50.7 - rt} 612 \cdot 10^{6} \cdot 90 dt \\
C_E &= \int_{0}^{50.7} e^{(0.036-r)t} 612 \cdot 10^{6} c_t dt + \int_{50.7}^{\infty} e^{0.036 \cdot 50.7 - rt} 612 \cdot 10^{6} c_{50.7} dt
\end{aligned}
\qquad (9)
$$

The sustainable price for the energy service from one barrel of oil today, resulting from using (8) and solving $C_X+C_H+C_E=R$ for P_s, would be $6.5/bbl and the depletion premium $2.1/bbl. If depletion of fossil fuels was the only concern with respect to the sustainability of the project, $2.1/bbl would be the appropriate depletion premium to be used in evaluating the project.

Next, a sustainability premium is calculated for the carbon dioxide constraint scenario. The sustainable price of energy services can be calculated for this scenario by equating the present value of revenues and costs under constrained extraction of fossil fuels. Revenues and costs of efficiency increases are the same as in equation (9). However, the costs of extracting oil and gas and producing hydrogen change according to the depletion scenario (see Table 4.1). Under the carbon dioxide reduction scenario, the sustainable price of one barrel of oil today would be $14.6/bbl (the sustainability premium, excluding extraction costs, would be $10.2/bbl). The sustainable price of $14.6/bbl reflects the depletion of fossil fuel as well as the carbon dioxide constraint.

A third scenario is calculated under which unlimited gas reserves are assumed. Hence, the extraction of gas would continue at the rate admissible under the carbon dioxide constraint even after year 86. The resulting sustainable price is $14.5/bbl. Hence, the depletion premium under the carbon dioxide constraint would be only $0.1/bbl (the depletion

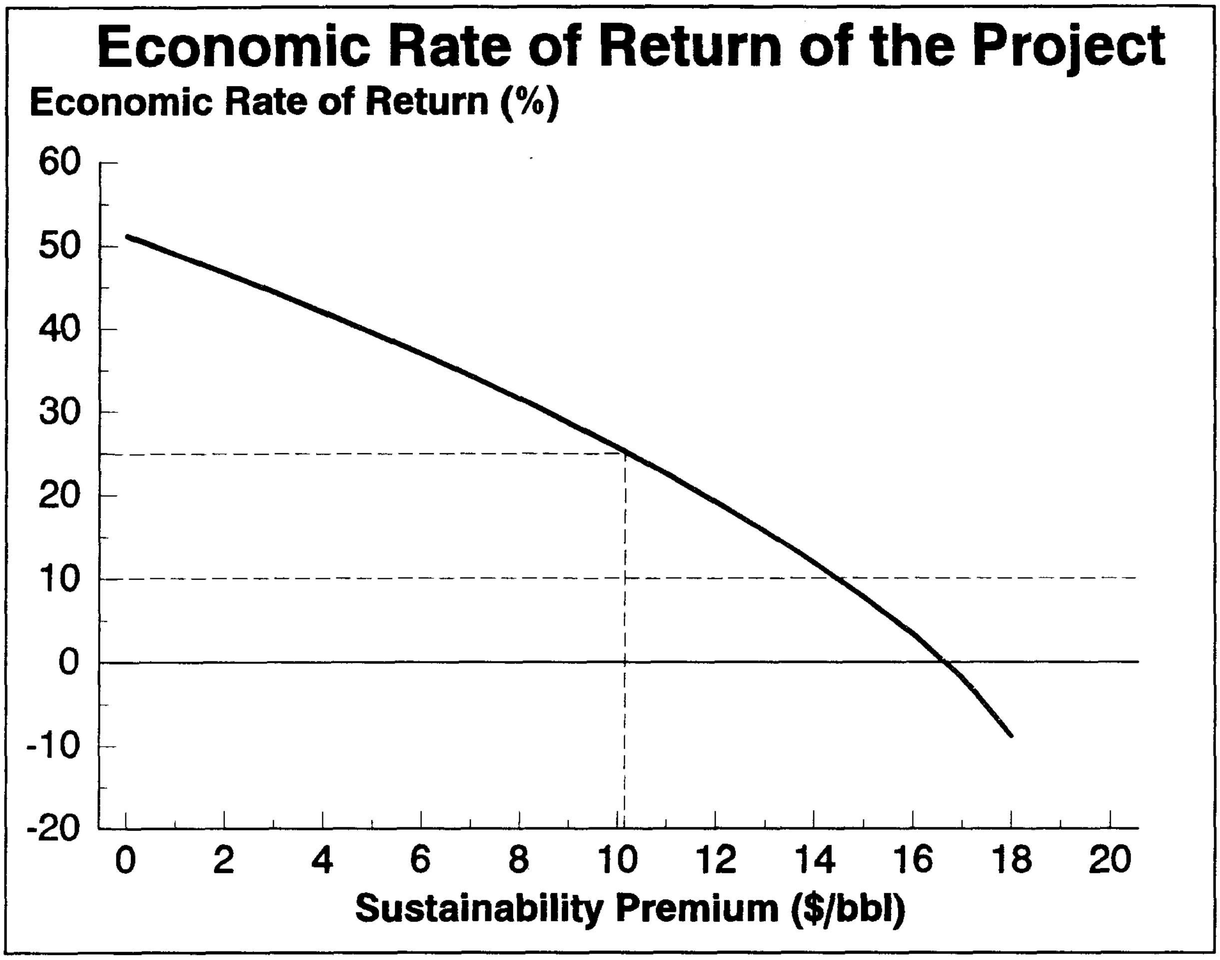

Figure 4.6 Economic Rate of Return with Sustainability Premium

premium is the difference between the sustainable price in a scenario with and without depletion constraint, respectively). This reflects the restrictions imposed on the use of fossil fuels by a carbon dioxide constraint. Hence, the appropriate sustainability premium on the depletion of the Oil field would be $10.1/bbl for unsustainable use of the atmosphere as carbon dioxide sink plus $0.1/bbl for unsustainable extraction as depletion premium. In terms of shadow prices, the market price of oil output needs to be reduced by $10.1/bbl for unsustainable use while an economic cost of $0.1/bbl of input (oil extraction) should be included. The equivalent sustainability premium per ton of carbon emissions would be about $77. The sustainability premia for the three scenarios are summarized in Table 4.2.

Evaluation Approach	Years until Depletion	Sustainability Premium ($/bbl) (5% ROR)	Sustainability Premium ($/bbl) (7% ROR)
Depletion Constraint Only	50.7	5.8	2.1
Carbon Dioxide Constraint Only	∞	13.5	10.1
Depletion and Carbon Dioxide Constraint	85.7	13.7	10.2

Table 4.2 Summary of Depletion Premia

Table 4.3 shows the calculations for adjusting the project's net benefit stream for the sustainability premium. At a sustainability premium of $10.2/bbl, the economic rate of return is reduced from 51.2% to 25.0% which is still above the assumed opportunity cost of capital of 12%. Under the assumptions made, the project would still be acceptable in the base case. However, the sensitivity to oil market price changes would be very large and might lead to rejection of the project. Now, a drop in oil prices by about $3.8/bbl would be sufficient to reduce the project's ERR to 12%. This could be considered unacceptable. Since the project's adjusted ERR is quite sensitive to several of the assumptions made, the ERR is plotted as a function of the depletion premium in Figure 4.6. For a sustainability premium of less than $14/bbl, the base case ERR would be above 12%. If the project was undertaken, actual compensatory investment in the supply of renewable energy and the increase in energy use efficiency would have to be made. If all compensatory investment was made out of the project's initial net present value (calculated without subtracting the opportunity costs of depletion) of $1.72 billion, $1.25 billion would have to be invested as compensation for

Year	Net Benefit Stream (mio $)	Oil Production (mio bbl)	Sustainability Premium ($10.2) (mio $)	Adjusted Net Benefits (mio $)
1990	-88	0	0	-88
1991	-319	0	0	-319
1992	-263	0	0	-263
1993	264	18.3	186.66	77.34
1994	614	36.5	372.3	241.7
1995	633	36.5	372.3	260.7
1996	657	36.5	372.3	284.7
1997	628	33.5	341.7	286.3
1998	587	30.1	307.02	279.98
1999	529	26.1	266.22	262.78
2000	457	21.7	221.34	235.66
2001	374	17.9	182.58	191.42
2002	304	14.7	149.94	154.06
2003	250	12.2	124.44	125.56
2004	204	10	102	102
2005	163	8.2	83.64	79.36
2006	127	6.6	67.32	59.68
2007	104	5.3	54.06	49.94
2008	82	4.3	43.86	38.14
2009	61	3.3	33.66	27.34
2010	44	2.5	25.5	18.5
2011	31	1.9	19.38	11.62
2012	20	1.4	14.28	5.72
2013	9	0.9	9.18	-0.18
Sum		328.4		
ERR	51.2%			25.0%
NPV (12% OCC)	1718		1255	463

Table 4.3 Adjusted Net Benefits with a Sustainability Premium of $10.2/bbl

depletion of the oil field and the atmosphere's absorption capacity for carbon dioxides.

5.4 Comments

Two complications arise from the point of view of national welfare maximization, especially if the unrealistic assumption of domestic consumption is eliminated. The country alone clearly has no incentive to curtail extraction of hydrocarbons according to a global carbon dioxide constraint. The decision to implement a global carbon dioxide constraint must be taken through international collective action; the sustainable pricing rule would merely be the tool for the implementation of such collective action. On the other hand, the required compensatory investment in sustainable substitutes points toward a sensible strategy on how the country can mitigate the negative consequences that global carbon dioxide emission limits would have for an oil exporting country. In particular, since the country is geographically well positioned for investment in solar hydrogen, such investment is suitable for compensating for the loss in revenues that would result from restrictions on carbon dioxide emissions in oil importing countries.

Also, if the oil was exported, the country would have little incentive to invest parts of the proceeds from the project in energy efficiency increases in other countries (presumably in industrial countries in which most oil consumption takes place). However, if all countries agreed on the use of a sustainability constraint, this apparent problem could be solved. If compensatory investment was required for consumption or depletion of natural capital in all countries, it would not matter in which country compensatory investment is undertaken since the market price would reflect the sustainability premium paid by the producing country. There would be a market price for "unsustainable oil" and another price for "sustainable oil" and the difference would be the sustainability premium. Hence, the country would obtain a higher price for sustainable oil (for which compensatory investment has been undertaken) than for unsustainable oil, and compensatory investment would be undertaken in the country in which it yields the highest return. As long as a sustainability constraint is not implemented globally, it would be the role of international lending agencies to promote, and support through concessionary lending, global thinking and the application of a sustainability constraint even if it is not in the interest of narrowly defined national welfare maximization.

6 Conclusions

The practical evaluation of natural capital depletion in projects shows a surprising lack of completeness and sophistication. Serious deficiencies prevail primarily with respect to the evaluation of land use, resource depletion and emissions from projects. The extensive literature on environmental evaluation and evaluation under uncertainty has obviously not yet fully penetrated practical project analysis. This neglect of environmental evaluation can be understood if it is considered that environmental impacts are often only considered a side aspect of the economic evaluation of a project. Moreover, theoretical evaluation methodologies often require data that is simply not available in the context of practical project evaluation in developing countries. On the other hand, neglect of environmental evaluation leads to a systematic and other significant bias against the conservation of natural capital. This highlights the need for developing and applying simple rules and methodologies for environmental evaluation, such as the sustainable supply rule presented in this chapter.

The case study in this chapter has shown that sensible estimates of shadow prices for natural capital can be derived from a sustainability constraint as a rule for evaluation under uncertainty. However, in order to improve the quality of environmental evaluation in project analysis, a more systematic approach is needed for those cases where conventional approaches for environmental valuation fail because of the involved uncertainty or implications for intergenerational justice. For example, generic shadow prices for various emissions should be derived from a sustainability rule. Such shadow prices would be based on physical flow models of individual pollutants. It cannot be expected that individual project analysts deal with the complexities of deriving all shadow prices for natural capital. It would be infeasible for the analysts of every energy project to concern themselves separately with complex models of global climate changes in order to arrive at a shadow price for carbon dioxide emissions. Therefore, it would be desirable to compile a "Sustainability Pricing Manual" for projects that would consist of practically applicable methodologies and estimates for important environmental shadow prices and could guide and improve the economic analysis of projects with environmental impacts.

The sustainable supply rule presented in this paper represents an application of the sustainability principle to the economic evaluation of natural capital depletion. It reflects a model of the economic system as subsystem of the biosphere and is based on limited substitutability between natural and human-made capital. This paper has established the requirements for appropriate shadow prices for natural capital depletion and the need for adequate intergenerational compensation. First, a shadow price below the price of a sustainable substitute should only be used if it can be shown, with reasonable confidence, that the costs are not higher. Second, rents from depletion of natural capital would have to be shared equally with all future generations. Third, sharing of rents should be accommodated through investment in sustainable functional substitutes. Furthermore, in order to be of practical use, the information requirements for the use of such a pricing rule should be limited.

By linking the shadow price of natural capital to the price of a sustainable substitute, the use of the sustainable supply rule would lead to a reversal of the default assumption that natural capital is a free good. Instead, the default assumption is that every unsustainable activity must bear the cost of its conversion to a substituting sustainable activity. The sustainable supply rule is suitable as a preemptive measure against the biases in evaluating natural capital. By using the sustainable supply rule, differences in relative scarcity of different resources would be appropriately reflected in the sustainable prices. The sustainable supply rule alleviates the intergenerational justice problem since the benefits from natural capital depletion are shared equally with all future generations. This is achieved by charging every generation a sustainable price for the services derived from natural capital. This sustainable price reflects the benefits all generations receive from depletion since it is below the initial cost of a sustainable substitute but, likely, above the current market price of the depleting resource. The rule is based on a semi-strong sustainability constraint that requires sustainability for groups of functionally substitutable types of capital. The intuition of this approach rests on the assumption that there is far less uncertainty about functional substitutability than about economic substitutability. The suggested rule is based on compensation through investment in sustainable functional substitutes. Finally, a major advantage of the sustainable supply rule is that information requirements for determination of shadow prices for natural capital depletion are moderate. The estimated lifetime of a resource, the cost of providing a sustainable substitute and the rate of return on specific compensating investment suffice to calculate the sustainable supply curve. Even without knowledge of the demand curve, the sustainable price can be determined iteratively until the market equilibrium lies on the sustainable supply curve. Furthermore, the rate of return on a specific compensating investment can likely be assessed more objectively and would be less controversial than the appropriate social discount rate to be used in conventional analysis.

Work in the area of ecological economics is exploratory in nature. A more technical analysis of the involved problems is called for. While the general approach for a sustainable supply rule is presented in this paper, more work has to follow in order to explore alternatives, resolve open theoretical questions and make the approach a workable one for practical evaluation. Remaining theoretical questions concern the definition of sustainable substitutes and functional substitutability. Since there is uncertainty about functional substitutability as well, the remaining risk of inadequate compensation needs to be addressed. An interesting extension would involve inquiry into the suitability of the proposed approach for a general shift from taxation of labour to taxation of natural capital, which has been proposed as an approach with intuitive appeal in a situation of high unemployment and environmental degradation. For this end, the overall impact of universal application of the suggested sustainability constraint on the economy would have to be assessed. Finally, the issue of population growth leaves unresolved questions on the appropriateness of the suggested distribution of resources between generations.

More practical issues to be addressed include the institutional arrangements for implementation of the intergenerational compensation schemes. Who undertakes and supervises the undertaken investment and to whom do the returns to such investment accrue? In a related paper (von Amsberg 1992), I try to show that the allocation of intergenerational property rights and creation of intergenerational markets can bring about the desired compensation through market mechanisms without huge government bureaucracies. The sustainable supply rule needs to be modified for practical cases such as heterogenous resources, substitutes with inelastic supply and gradual phasing-in of the sustainable substitute. Similarly, transition toward a sustainable technology could occur in several steps. In more complicated examples, the sustainable supply rule remains applicable in principle, however, the appropriate equations need to be worked out to guide the practitioner in such instances.

This chapter does not explicitly address the issues of <u>intra</u>-generational justice even though implementation of a sustainability constraint would have profound implications for the allocation of resources within the living generation. Most compensating investment would have to be undertaken by industrial countries with the highest amount of unsustainable consumption. On the other hand, many opportunities for compensating investment with the highest return would likely be in developing countries. This could motivate an increased resource flow from industrial to developing countries. Intra-generational equity concerns could be addressed explicitly by modifying the sustainable supply rule such that sustainable supply of a resource would be required not at the current level of consumption but at the increasing level of consumption resulting from higher consumption in developing countries. Then, sustainability would ensure that consumption takes place at a level that can theoretically be achieved in all countries and would resolve the dilemma that ecological disaster would likely follow if all countries achieved the level of material consumption that is currently enjoyed in the industrial countries. Hopefully, this chapter stimulates thinking and contributes to the definition and implementation of a sustainable development path for industrial as well as developing nations. If the present generation uses its resources to invest in research, development and implementation of sustainable technologies and initiates the transition toward a sustainable economy, we will hopefully not have to bear the responsibility for having impoverished this planet for generations to come.

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