Project Evaluation and the Depletion of Natural Capital: An Application of the Sustainability Principle

Joachim von Amsberg

February 1993

Environment Working Paper No. 56

This paper has been prepared for internal use. The views and interpretations herein are those of the author(s) and should not be attributed to the World Bank, to its affiliated organizations or to any individual acting on their behalf.
ACKNOWLEDGEMENT

The author is an instructor at the University of British Columbia, Faculty of Commerce and Business Administration, in Vancouver, Canada. The research leading to this paper was partly funded by a contract from the World Bank’s Environment Department. The author wishes to acknowledge very helpful comments by and encouraging discussions with James A. Brander, Herman E. Daly and Robert J. Goodland. Valuable comments were also provided by Salah El Serafy, Bryan Routledge and David Wheeler. Of course, the author retains responsibility for the expressed opinions and possible errors.

Departmental Working Papers are not formal publications of the World Bank. They present preliminary and unpolished results of country analysis or research that are circulated to encourage discussion and comment; citation and the use of such a paper should take account of its provisional character. The findings, interpretations, and conclusions expressed in this paper are entirely those of the author and should not be attributed in any manner to the World Bank, to its affiliated organizations, or to members of its Board of Executive Directors or the countries they represent.

Because of the informality and to present the results of research with the least possible delay, the typescript has not been prepared in accordance with the procedures appropriate to formal printed texts, and the World Bank accepts no responsibility for errors.
ABSTRACT

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 the large uncertainties about the functioning of the biosphere. In addition, decision making is systematically biased against the interests of future generations. Inter-generational 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, 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 paper 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. The sustainability constraint should be reflected in the shadow prices used to evaluate natural capital depletion. From the sustainability constraint, a sustainable supply rule is derived that is operational and 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. While the approach has been developed for project analysis, it is easily extended to the determination of an appropriate resource tax. The analysis of several recently appraised World Bank projects shows a very low level of completeness and sophistication in the evaluation of environmental costs. In particular, most project analyses do not include a depletion premium for the extraction of a natural resource. Deficiencies are also prevalent in the determination of an opportunity cost for land and of the damage from air pollution generated by the project. The sustainable supply rule is applied to several of these World Bank projects and the impacts for the evaluation of the selected projects is shown.
# Project Evaluation and the Depletion of Natural Capital: An Application of the Sustainability Principle

## Table of Contents

**EXECUTIVE SUMMARY** ............................................................... i

1 Introduction ................................................................. 1

Part A: **Deficiencies in the Conventional Evaluation of Natural Capital Depletion** ............. 3

2 Problems with Market and Shadow Prices of Natural Capital .................................. 4
   2.1 Lack of Reliable Market Prices for Natural Capital ..................................... 4
   2.2 Difficulties with Shadow Pricing Natural Capital ...................................... 8
   2.3 A Better Default Value for Natural Capital ............................................... 9

3 **The Inter-generational Problem** ............................................................................. 10
   3.1 Inter-generational Justice .............................................................. 11
   3.2 Caring for Future Generations as Public Good ........................................ 13
   3.3 Just Distribution of Resources between Generations .................................. 14

Part B: **Sustainability and Project Evaluation** ..................................................................... 17

4 **The Appropriate Sustainability Constraints** ......................................................... 17
   4.1 Strong and Weak Sustainability .......................................................... 17
   4.2 The Geographic Scale of Sustainability ................................................. 22

5 **Shadow Prices Under a Sustainability Constraint** ................................................. 23
   5.1 The Sustainable Supply Rule .............................................................. 23
   5.2 Application of the Sustainable Supply Rule ........................................... 27

Part C: **Sustainability and Project Evaluation: Case Studies** ..................................... 30

6 **Detailed Case Studies** .......................................................................................... 32
   6.1 Nigeria: Oso Condensate Field Development Project .................................. 33
   6.2 Malawi: Second Wood Energy Project ...................................................... 44
   6.3 Yemen: Land and Water Conservation Project ........................................... 49
   6.4 Jamaica: Clarendon Alumina Production Project ........................................ 51
   6.5 Ivory Coast: Fifth Oil Palm Development Project ......................................... 54

7 **Summary of the Treatment of Natural Capital Depletion in Other Bank Reports** .... 55

8 **Conclusion and Extensions** .................................................................................. 60

Appendix A Derivation of the Sustainable Supply Curve .............................................. 63

Appendix B Comparison with the El Serafy-Mikesell Approach ..................................... 65

References .................................................................................................................. 67
EXECUTIVE SUMMARY

Sustainability is becoming an almost universally accepted policy objective. However, there remains considerable controversy about the precise meaning and the applicability of the sustainability concept. This paper seeks to summarize the need for a sustainability constraint on economic activities and develop a methodology for reflecting a sustainability constraint in the economic analysis of projects. The need for a sustainability constraint is based on the recognition that, over the last century, human activities have increased dramatically in scale. As a result, we have moved from a relatively empty world to a relatively full world in which human activities are large in scale compared to the size of the ecosphere. Crowding effects, which could be ignored in the past, are now prevalent and require adjustment of the conventional economic decision making tools. The two, arguably, most significant crowding effects arising from the depletion of natural capital (encompassing the depletion of natural resources, the disposal of waste products and damages done to the natural life support systems) are the pervasiveness of external costs and the impacts of activities in the present on the welfare of future generations. The following discussion will show how, in the presence of these two crowding effects, conventional evaluation of natural capital depletion in cost-benefit analysis is deficient and how the deficiencies can be overcome.

The first problem with conventional evaluation of natural capital is the existence of biases that lead to systematic under-valuation of natural capital through market and shadow prices. Many types of natural capital have the properties of a public good. Therefore, reliable market prices often do not exist. Even if market prices for natural capital exist, they under-value natural capital since many benefits from natural capital are pervasive and cannot be captured by the owner. Moreover, politicians, corporate executives and other decision makers often face short-term incentives that leads to the use of an implicit discount rate above the social discount rate and excessive depletion as well as prices lower than in the social optimum. For these reasons, natural capital usually needs to be shadow-priced; however, conventionally derived shadow prices under-value natural capital as well. Even though there exists an extensive body of theoretical literature on evaluation under uncertainty, the required information is usually not available in a real-life situation and the level of sophistication in practical project evaluation is often low. In practice, shadow prices for natural capital depletion are based on an enumeration of known damages arising from depletion, and no provision is made for yet unknown costs arising from the depletion of natural capital. Since many benefits from natural capital are pervasive, and human knowledge of these benefits is incomplete, shadow prices based on known damage only systematically under-value natural capital.

Positive enumeration of known damages from natural capital depletion is equivalent to the use of a zero default value, in the absence of any knowledge about the benefits from natural capital. The assumption of zero costs for the depletion of natural capital in the absence of knowledge about specific damage is inconsistent with past experiences with unexpected damage arising from depletion of natural capital, such as the emissions of chlorofluorocarbons and carbon dioxides. The conventional approach also ignores our understanding that the natural environment is the result of an evolutionary process that deserves some benefit of doubt in favour of its existence. To remedy the systematic undervaluation of natural capital, it is suggested that the default assumption of natural capital as a free good be replaced by the default assumption that every unsustainable activity has to bear the cost of converting it to a sustainable activity in the long run. In the absence of better knowledge, the default value for natural capital depletion would be the cost of a sustainable substitute. In face of fundamental uncertainty about the functioning of the ecosphere this procedure would represent a more cautious and prudent approach. The burden of proof would be reversed such
that natural capital is only depleted if it can be shown that depletion makes us better off. The conventional approach leads to depletion of natural capital unless it can be shown that depletion makes us worse off. Due to paramount uncertainty, the difference between the two approaches is essential.

The second problem with conventional evaluation is that it ignores the inter-generational welfare impacts of natural capital depletion. Future markets between generations are necessarily incomplete. Therefore, markets do not bring about efficient inter-generational allocation of the risks arising from natural capital depletion. Moreover, recent economic research shows that current prices, including the prices for natural capital and the social discount rate, depend on the assumption about which generations own the resource stocks. For every possible distribution of resource ownership across generations, there is a different efficient resource depletion path. Market prices would be correct indicators of economic value only if the assumptions about inter-generational resource distribution were explicitly accepted. However, the current generation has an incentive to assume ownership of all resource stocks. Under this assumption, the efficiency of resource markets does not ensure any minimum level of welfare for future generations. Therefore, the assumptions made by the current generation about resource distribution would be unacceptable and future generations would need to be explicitly compensated for the depletion of natural capital. In order to provide adequate compensation in face of large uncertainties, future generations would have to be compensated for resource depletion through investment in sustainable substitutes for the depleted resource.

The concerns about inter-generational justice and under-valuation of natural capital due to uncertainty can be overcome by imposing a sustainability constraint on the economic activities of the current generation. Such a sustainability constraint would lead to implementation of an inter-generational compensation mechanism for resource depletion and an intuitive appealing approach to inter-generational distribution of resources. Under a sustainability constraint, every generation would be required to leave natural capital intact in the sense that it retains the ability to generate an equal stream of benefits in perpetuity. Since there exists considerable uncertainty about long-term substitutability between different types of capital, natural capital would have to be left intact such that constant streams of the services derived from it can be obtained by every generation at the same real cost. Hence, compensation for the depletion of natural capital would have to be made through functional substitutes. For example, the depletion of fossil fuel deposits would require compensation through investment in renewable energy sources. Subsequently, the price of fossil fuel depletion would reflect the cost of converting energy supply to sustainable substitutes in the long-run.

The following discussion relates the sustainability constraint to the practical evaluation of projects that contribute to the depletion or restoration of natural capital. There is no reason why an individual project would have to be made sustainable. It is perfectly acceptable to have projects that generate positive net benefits for a limited time only as long as all economic costs and benefits of the project are properly accounted for and future generations are compensated for any costs imposed on them. However, problems with conventional project evaluation arise because, as discussed above, prices are distorted by a) the pervasiveness of benefits from natural capital and the incompleteness of knowledge about these benefits leading to systematic under-valuation of natural capital; and b) the unacceptable assumptions made by the current generation about the inter-generational distribution of resource ownership. If a sustainability constraint was imposed to address these problems, the appropriate shadow prices to be used in project evaluation would change and, in this way, impact on the evaluation of projects.
If a sustainability constraint was implemented at a global or national level, market prices would already reflect this constraint and could be used as prices in project evaluation. As long as a sustainability constraint is not yet implemented at a higher level, however, shadow prices derived from a sustainability constraint need to be calculated and used at the project level. Also, the appropriate inter-generational compensation for natural capital depletion needs to be calculated and implemented. Under a sustainability constraint, shadow prices for the depletion of natural capital can be derived from the sustainable supply rule that requires that the depletion of natural capital be evaluated at the sustainable price. For a natural resource, the sustainable price is the cost at which the services from the depleted resource can be provided through a sustainable substitute in perpetuity if, for every unit of the depleted resource, the sustainable price is invested into the production of the sustainable substitute. This rule reflects the sustainability constraint as well as the cautious approach that suggests the cost of a sustainable substitute as the default value for natural capital depletion.

In several case studies, the sustainable supply rule is applied to recently appraised World Bank projects. For example, the sustainable price for oil from an extraction project in Nigeria is calculated. If all of Nigeria's hydrocarbon reserves, the expected increase in global energy demand and expected increases in energy use efficiency were taken into account, the sustainability premium would be about $2 per barrel of oil extracted (assuming a 7 percent real rate of return on compensatory investment). If in addition a global carbon dioxide emission constraint was taken into account, the sustainability premium would be about $10 per barrel of oil. With this sustainability premium the economic rate of return of the project would be reduced from 51.2% to 25%. (The original analysis does not include a user cost for resource depletion.) The case studies show how, with the implementation of a sustainability constraint, the desirability of projects would shift from natural capital depleting projects to those which restore natural capital, i.e., investments in energy or water use efficiency or reforestation projects.

The economic analyses of several World Bank projects, which were appraised over the last decade, have been examined with respect to their treatment of the depletion of natural capital. The analyzed reports show a surprising lack of completeness and sophistication of environmental valuation in the economic analysis of Bank projects. 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 penetrated practical project analysis. This neglect of environmental evaluation can be understood if it is considered that environmental impacts are often 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 practical context of project evaluation in developing countries. On the other hand, neglect of environmental evaluation leads to a systematic and, as some of the case studies show, a 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 discussed in this paper.

One of the recurrent issues in the analysis of Bank reports is the treatment of natural capital as a free good. Many projects use natural capital as an input but do not include a corresponding user cost in the economic analysis. In most projects that involve depletion of a natural resource, such as mining or oil/gas development projects, no user cost or depletion premium is included in the calculation of economic project costs. Considering the extensive discussion of user costs in more theoretical World Bank publications, this practical deficiency is surprising. In other 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. While, in many cases, it may turn out that the depletion premium for the extraction of a natural resource is small, it should, nevertheless, always be explicitly considered. In the case studies, the sustainable supply rule is used to determine an appropriate depletion premium.

In many 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. Under a sustainability constraint this assumption would be unacceptable in most instances. The lack of observable commercial uses would be insufficient for the assumption of zero opportunity cost of land, especially if the project does not only use but also degrade the land. Most land serves many functions beyond their obvious commercial use, including use for various subsistence activities. In an increasingly crowded world, remaining wilderness areas are important for preserving biological diversity. While the ecological value of wildlands would differ considerably, assigning a value of zero would be justified only in extreme and rare circumstances. The approach suggested for the determination of economic land value in the absence of apparent commercial uses or a reliable market price is to consider the replacement costs. This would be the cost of rehabilitating or restoring similar lands that are already degraded. Thus, a project would carry the cost of maintaining the stock of productive land or wilderness areas by rehabilitating or restoring a degraded area of equal size. Consequently, a mining project would have to bear 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.

With few exceptions, the damage costs arising from emissions are not included in the economic analysis of Bank projects even though possible damages from emissions are often acknowledged in the reports. Generally, carbon dioxide emissions are not even mentioned in the analyzed reports. One justification for omitting damage costs from emissions could be the considerable uncertainty about these damages. Omission, however, is clearly an inappropriate treatment of uncertain costs. The expected value of damage costs for most emissions would be strictly greater than zero and an explicit evaluation of expected damages is preferable even under significant uncertainty. If expected damage costs are significant, sensitivity analysis should be provided for further information. 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 could be reduced if it can be shown that damage costs are less in a specific instance. A second justification given for omission of damage costs from emission is that a project includes pollution abatement technology, and the remaining emissions do not exceed international emission standards. 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.

The case studies in this paper show that sensible estimates of shadow prices for natural capital can be derived from a sustainability constraint as a rule for project evaluation under uncertainty. However, in order to improve the quality of environmental evaluation in project analysis, a more
systematic Bank-wide approach is needed for projects where conventional approaches for environmental valuation fail because of the involved uncertainty or implications for inter-generational justice. It is probably unrealistic to expect that individual project analysts will deal with the complexities of deriving shadow prices for natural capital from scratch. For example, it would be infeasible for the analysts of every energy project to concern themselves 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 World Bank 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. Similar to the World Bank Commodity Price Forecasts, this manual would provide project analysts with generic shadow prices. These sustainability prices would be derived from a sustainability constraint for the depletion of various resources and for various emissions in different regions.
Introduction

World Bank economists have made important contributions to the natural resource economics literature. Consequently, several World Bank publications and sector studies include a discussion of user costs or depletion premia for various natural resources. It is surprising to note, however, that in the economic analysis of most individual World Bank projects which contribute to the depletion of a natural resource, a user cost is not included. 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. Clearly, the neglect of the opportunity costs of natural resource depletion represents an incorrect economic analysis. If lending decisions were based on the economic rates of return of projects, this neglect would bias the lending program in favor of resource depleting projects. The observation that user costs are often ignored in practical analysis raises several complex questions about the reasons for this neglect and how, in fact, they should be calculated for the purpose of project evaluation. The goal of this paper is to provide an operational rule for determining a shadow price for the depletion of a natural resource as well as determining the appropriate compensation of future generations for the depletion.

The question about evaluation of non-renewable resources leads to the broader question of how depletion of natural capital should be adequately treated in economic evaluations such as cost-benefit analysis. In this paper, natural capital is defined as all stocks, in a broad sense, that yield a flow of natural resources and natural services. Natural capital encompasses stocks of non-renewable resources, such as oil, gas and mineral deposits and renewable resources, such as forests and fisheries. It also includes the biosphere's capacity to sustain human life and economic activities through, for example, provision of clean air, water and a limited capacity to absorb waste products. The biosphere as both a source of materials and energy and a sink for waste products represents natural capital. 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. However, like human-made capital, natural capital is more than an arbitrary aggregation of assets. It is a complicated web of interrelations between assets and processes that can provide a wide variety of services to humans. While sustainable human activities are those which use natural capital within its capacity to regenerate, this paper deals with activities that go beyond that limit, deplete natural capital and, hence, reduce the earth's capacity to serve as source and sink for welfare generating activities in the future.

A large body of literature deals with the economic theory of exhaustible resources. Most importantly, the user cost concept has been introduced by Hotelling (1931) and more recently summarized with many extensions by Dasgupta and Heal (1979). However, many widely used models of neoclassical economic analysis and practical economic analysis tools are characterized by neglect of natural capital as a factor of production. Many simplistic models of the economy consist of circular material and monetary flows that, in principle, have no quantitative limits. Households supply firms

---

1 See Part C of this paper for several examples.

2 See Samuelson and Scott (1980), p.190 for a typical graphical depiction of this model.
with the factors of production and receive goods and services in return; firms pay factor income to households and receive payment for goods and services. Human-made capital is considered the ultimately scarce factor of production while infinitely elastic supply of natural resources is implicitly assumed. The resulting default assumption for any good that is not part of the circular flow, and therefore does not have a market price, is that it is a free good.

A purely circular model of the economy is certainly faulty since the second law of thermodynamics implies some irreversibility in all material processes. Almost all economic activities, even those that appear to be environmentally beneficial such as recycling, contain irreversible physical processes: entropy increases and the amount of useful energy in the system decreases. While the efficiency in using natural capital can be increased, physical laws place an absolute limit on the increase in efficiency and the substitution of human-made capital for natural capital. Therefore, in addition to circular monetary and material flows, there exists a finite stock that is depleted. Since the economy is a subsystem of the biosphere with definite quantitative limits, the material flows in the economy cannot grow infinitely. Of course, the fact that irreversibility exists and that material flows have an absolute limit does not imply that the assumptions of neoclassical models are bad. In fact, they were useful simplifications at the time when those models were developed. The world was still relatively empty and economic activities were small in scale. The physical flows induced by economic activities had not yet achieved significant effects on the biosphere and the scale of the irreversible streams was small enough not to impact significantly on the options available to future generations. However, strong indications are emerging that we are moving from an "empty world" to a "full world" [see Daly (1991)]. Today, humans use about 40% of the net primary product of land-based photosynthesis [see Vitousek et.al.(1986)]. The increasing evidence of long-term, and often irreversible, global environmental impacts of human economic activities were recently summarized in the Brundtland Report [World Commission on Environment and Development (1987)]. Given the indications of an increasingly crowded world, foolproof evidence is not required to make the consideration of a modified economic model, resembling physical realities more closely, worthwhile.

In a modified view, the material flows of the economy are only a subsystem of the biosphere. Material flows in the economy are linked with and limited by the size of the biosphere. While we do not know the precise location of these limits, we know that they exist. Matter and energy from the biosphere are used in the economic system and waste and entropy is released. By the second law of thermodynamics, the flows of useful energy from the biosphere into the economic system and the flows of waste products back into the biosphere are irreversible. The only relevant link of the biosphere with the universe, is solar energy as a steady flow into the biosphere. All material and energy flows into and waste flows out of the economic system are unsustainable unless they are based on solar energy as the only source of negative entropy in the biosphere. With this modified view of the economy, material and energy flows, as well as capacities to dispose of waste, are not free goods. Any unsustainable activity would have to be replaced by a sustainable activity in the long run.


---

3 For a detailed discussion of such a model of the economy see Colby (1990), p.23 ff.

4 Of course, this is a simplifying assumption in itself since, strictly speaking, the sun has a finite energy supply. Nevertheless, this assumption seems justified considering the long expected lifetime of the sun compared to any sensible human planning horizon.
(1991) and others [see Costanza (1991)] have established a new branch of economic research that attempts to integrate economic modelling with the limits of the physical realities. At the level of policy analysis, El Serafy (1989) presents an application of these considerations to National Income Accounting. Similarly, Barbier, Markandya and Pearce (1990) discuss the relation between physical environmental constraints and cost-benefit analysis. While related in spirit to Barbier, Markandya and Pearce (1990), the present paper provides a broader discussion, a more operational methodology and several practical case studies. The paper draws from El Serafy's contribution and applies it to the shadow pricing of natural capital depletion.

The goal of this paper is to show how economic analysis tools that were developed for an almost empty world, can be adjusted in order to be useful for analysis in a full world. This paper presents a method for evaluation and comparison of projects or policies that involve depletion of natural capital whether in the form of depletion of a non-renewable resource, over-exploitation of a renewable resource or exhaustion of the biosphere's capacity to absorb waste. In part A of the paper, I summarize and discuss the deficiencies of conventional analysis of natural capital depletion. It will be shown that, due to various market failures, the cost of natural capital depletion is likely to be underestimated. It will be argued, based on principles of inter-generational justice, that adequate compensation of future generations for the depletion of natural capital is required. The discussion in Part B 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 proposed "sustainable supply rule" would allow derivation of a sustainable price for the depletion of natural capital which should be used as shadow price for natural capital depletion in project analysis. Part C presents several case studies of recently appraised World Bank projects. The original economic evaluation of the project is analyzed and an application of the sustainable supply rule provided as an alternative approach.

For illustrative purposes, I will refer to the following simple example of natural capital depletion throughout the paper. Country "Dryland" has only limited non-renewable ground water resources and no surface water. The government of Dryland is considering an agricultural development project which would use the non-renewable ground water resource for irrigation. Treating ground water itself as a free resource (considering only the costs for pumping the water to the surface) the project has a positive social net present value (NPV) and should be undertaken. On the other hand, if the project would have to rely on sustainable water sources (imported water, desalinized seawater, etc.) the project's NPV would be negative. The operational method proposed in this paper is used to determine the value of this project and make a decision whether this project should be undertaken.

Part A: Deficiencies in the Conventional Evaluation of Natural Capital Depletion

Following conventional resource economic analysis in a world without extraction costs and without uncertainty, 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 a rate equal to the economy's interest rate [see Hotelling (1931)]. Similarly, the price of a renewable resource would have to change with the interest rate minus the natural rate of growth or regeneration 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 price 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. This implies that earlier generations would have available large quantities of the resource at a low price and could, hypothetically, invest a portion of the rents derived from the resource such that no other allocation of the resource would make all generations better off. In a world with perfect markets for natural capital (under uncertainty including complete forward markets), the same result would be brought about by market mechanisms.

If the aquifers in Dryland were privately owned and there was a perfect market for water, the appropriate shadow price for water extraction under conventional analysis would be the market price of in-situ ground water. The project should be undertaken whenever the social benefits from the water use minus extraction costs exceed the market price of ground-water. If there was no perfect market for water, depletion would have to be shadow priced by determining the appropriate user cost. This user cost would be the discounted cost of procuring water from other sources after depletion (the backstop technology). If the cost of the backstop technology is higher than the benefit from water use, the backstop technology would not be used and the appropriate user cost would be the discounted future net benefits from water use foregone because of depletion. The project would be considered worthwhile whenever the price of water in situ is expected to rise at less than the rate of interest. This is intuitively convincing since with a user cost expected to rise at less than the rate of interest, it would be profitable to convert water to money which is growing in value faster than water is. On the other hand, if the user costs was expected to rise at more than the rate of interest, it would be better to leave the water in the ground (not to undertake the project) where it is growing in value faster than money.

There are a variety of reasons why evaluation of depletion of natural capital with conventional methods is deficient. In Section 1, I will abstract from issues of inter-generational justice and 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. Second, the inherent incompleteness of shadow prices for natural capital due to the uncertainty about long-term costs will be demonstrated. Section 3 will address the special concerns arising from the inter-generational problem with respect to depletion of natural capital. Sections 2 and 3 together demonstrate the need for a sustainability constraint on economic activities which would have to be reflected in economic evaluation.

2 Problems with Market and Shadow Prices of Natural Capital

2.1 Lack of Reliable Market Prices for Natural Capital

A person who invests in human-made capital would ensure that property rights for the investment are established and that markets exist on which the capital and outputs of the investment can be exchanged 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 difficult since many natural resources have typical public-good characteristics. These resources include fisheries, public rangelands, ground-water and the absorption capacity of air and water. Without institutions to alleviate the market failure, use of these resources generates external costs that are not considered in individual decision making. However, institutional arrangements are costly. Even
where institutional arrangements are made and property rights are assigned, they are often less secure than those for other assets. Furthermore, governments may not have the institutional strength to restrict access to common property resources, resulting in inefficient over-usage and under-pricing of the resource. In the example of ground-water depletion, it may be infeasible for the government of Dryland to enforce regulations restricting the drilling of wells and the extraction of ground water above the desired rate of extraction.

When production causes the depletion of natural capital, and the costs of depletion are not included in the product's price due to lacking market, an environmental externality exists. Externalities can be remedied by, for example, Pigou taxes or introduction of trade with emission certificates [see Baumol and Oates (1988)]. However, these instruments are rarely used. Public decision makers seem to have little incentive to implement policies for 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 easier than for a large number of damaged individuals who would suffer from the costs of organizing and coordinating their collective lobbying efforts. Facing intense lobbying by the polluters, politicians can use manifold uncertainties and the significant information requirement for determining external costs as justifications for delaying effective action. 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 consistent underestimation of external costs.

Implementation of institutional arrangements for overcoming currently observed market failures is not sufficient. 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 or other regions or countries. This continuous and pervasive incentive to invent new ways of depleting natural capital costlessly 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.

Even when markets for natural capital exist, the market price is likely to underestimate the social opportunity cost of resource depletion. The opportunity costs of depletion are the discounted future benefits foregone because of depletion. Hence, the opportunity 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. 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

---

5 For an overview of the arguments see the Introduction in Lind et al. (1982).
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. The social return on investment
does not equal private returns because of the existence of externalities 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).
Lacking or incomplete internalization of external effects means that market forces would equalize
private but not social rates of return on investment. 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.

Second, market interests rates are based on the decisions of short-living individuals who seem
to have 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 inter-generational
time. While a moderate decrease in well-being during one’s lifetime may 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. Social time
preference should, therefore, be lower than individual pure time preference, at least when applied
to periods that exceed human lifetime.

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, since 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, an ethical problem arises. The
discount rate may, for example, affect the decision about the required lifetime of nuclear waste
containers. Discounting for 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.

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 may be forced to increase depletion
and export of natural resources at a depressed price because a resource price decline has led to a liquidity crisis for the resource depleting country. This would explain the increased 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 abundant evidence of resource owners' behavior that is inconsistent with profit maximization. When resources are owned by governments, extraction licenses are often granted through tender and bidding procedure that do not take inter-temporal welfare maximization into account and encourage excessive extraction. Private owners of a natural resource often do not maximize discounted profits but instead some short term income measure. Extraction companies appear to have revenue targets, increasing output when prices are depressed, which is socially and privately sub-optimal.

Behavior 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' chance of reelection depends on publicized GNP figures and other related income measures that wrongly omit accounting for natural capital depletion, they would have an incentive to maximize (incorrectly measured) GNP rather than social benefits 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. Hence, under the conditions that, first, decision makers within a corporation maximize not company profits but personal utility, second, their tenure is shorter than the time span over which their decisions have impact 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 that are reflected in financial statements, opportunity costs may be hidden from the principal (the shareholders or the electorate) relatively easily.

Correspondingly, managers in lending agencies, such as the World Bank, face incentives that are biased toward achieving short-term benefits due to the difficulties involved in introducing a system of personal long-term accountability. The incentives of project managers may explain why the cost-benefit studies of many extraction projects do not include a use cost. As mentioned before, the World Bank frequently includes the full resource rent as a benefit in the calculation of economic rates of return for extraction projects. Such evaluation clearly biases investment decisions toward projects that are depleting natural capital and reflects an implicit discount rate higher than the social discount rate. If project economists, managers and politicians ignore or underestimate user costs, the supply of extracted natural resources will be higher then in the perfect market equilibrium. In aggregate, this effect is likely to be non-marginal and would depresses market prices for such 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. Even if
policy makers desire implementation of efficient policies, it is difficult to establish markets for natural capital due to the public 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.

2.2 Difficulties with Shadow Pricing Natural Capital

Due to the lack of correct market prices, the depletion of natural capital needs to be shadow priced in order to evaluate a depletion project. The shadow price of natural capital is its opportunity cost or the value of natural capital in its next best alternative, present or future use. Determining this shadow price is a difficult task since for all 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 future price of the resource, after depletion, has to be estimated.

The opportunity cost of depleting a stock of a natural resource is generally recognized as the user cost which is the discounted value of potential future benefits foregone through current depletion [see Hotelling (1931)]. The applicability of the opportunity cost concept to all other types of natural capital depletion is less recognized. Depletion excludes or diminishes the potential benefits from identical or alternative activities now or in the future and, hence, implies a social opportunity cost that should be reflected in the shadow price. For example, the first factory polluting the air in a specific area may not cause any environmental damage. If, however, a second economically feasible factory would cause such damage, 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 production factor is natural capital in the form of the limited absorption capacity of the natural environment. As the example shows, in a world with discrete investment opportunities, costs for use of the environment can accrue even in the absence of environmental damage. 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.

On top of the discussed difficulties in choosing a social discount rate, shadow pricing of natural capital is seriously impaired by other problems. The services rendered by natural capital are pervasive and very difficult to evaluate completely. The opportunity cost of clear-cutting a forest includes all benefits that could be derived from the standing forest in perpetuity. 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 release of 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, uncertainty about cultural and technological development of humanity is so great that future economic values of resources are impossible to estimate. Too many unexpected events and potential discoveries lie ahead to make any sensible estimation of resource values hundreds of years ahead. For such Knightian uncertainty (this refers to uncertainty where the probability distribution of an uncertain parameter
is not available) conventional economic tools for decision making under uncertainty, such as expected utility theory, fail.

Recently, economic techniques for calculating shadow prices have become more sophisticated. For the treatment of uncertainty the concept of option value (or risk premium) has been developed [see Cichetti and Freeman (1971)]. Irreversibility can conceptually be included by adding a quasi-option value [see Arrow and Fisher (1974)]. However, practical applicability of these concepts is still very limited. Moreover, conceptual limitations remain since none of these instruments deals sufficiently with Knightian uncertainty and technological progress. Moreover, most of the more sophisticated evaluation techniques are rarely used in practice due to the involved effort that does not seem to be justified in light of general data imprecision. As a result, evaluation of the opportunity costs of natural capital depletion is 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 explicitly considered. On the other hand, the benefits from depletion are included more or less completely since they are captured by the market for the output product (steal, pulp, electricity and others). Thus, conventional shadow pricing of natural capital depletion implies a systematic underestimation of its economic value.

2.3 A Better Default Value for Natural Capital

The conventional approach to evaluation implies that the default value of natural capital, in the absence of any knowledge, is zero. If market prices are used, the value is zero unless property rights have been established and can be enforced. As noted, establishment of property rights is often not possible or very costly. If shadow prices are used, the value is zero unless the existence of opportunity costs can be shown explicitly. As discussed above, the pervasiveness of the benefits from natural capital and lacking human knowledge would almost always allow parts of the opportunity costs to go unnoticed and conventional analysis implies a systematic downward bias for the value of natural capital. This neglect of natural capital in economic evaluation strongly conflicts with the fact that the earth’s natural capital is the result of millions of years of evolution and should be viewed as a proven system that deserves protection. This argument is not directed at sentiments about natural beauty. Rather, it is directed at our prudence to understand that natural capital is not an arbitrary accumulation of natural resources but a complicated web of interactions that has emerged from millions of years of evolutionary competition. Since we do not fully understand the functioning of the natural systems, natural capital in its original form deserves considerable benefit of doubt for its existence. Past experiences of unexpected negative consequences of interference with natural systems (ozone layer depletion, greenhouse effect etc.) would suggest that a more cautious approach with respect to depletion of natural capital is in our own interest. Such a cautious approach would reflect the expectation of unpredictable costs arising from the depletion of natural capital.

Implementation of a more cautious approach to natural capital depletion would not imply that all natural capital must be left untouched. Rather, a reversal in the burden of proof is suggested. Conventional evaluation 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 full of uncertainties. In millions of years, 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 very fundamental ways. Therefore, it would only be acceptable to change the composition of the atmosphere (for example by increasing
the carbon dioxide concentration) 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, conventional analysis would suggest to pollute the atmosphere until we find out that the damage that results from this change in the atmosphere outweighs the benefits. We are currently learning about the functioning of the biosphere by trial and error. However, due to the increasing human population and our ability to amplify our impacts on the environment through technology, the stakes in this trial and error game have grown so large that the process is 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.

The mechanism by which I suggest to reflect the reversal in the burden of proof goes back to John Ise's (1925) proposal to evaluate a non-renewable resource at the price of a renewable substitute. Hence, in the absence of better knowledge, the default value for the depletion of natural capital should be the cost of a sustainable substitute. This means, depletion of natural capital has to be made as expensive as a sustainable substitute, unless it can be shown that the full economic cost of natural capital depletion is less. While 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. This is in contrast to conventional analysis that would begin with a default value of zero for a presumably free good. As unexpected damage arises and the resource becomes scarce, the cost of natural capital depletion would be increased step by step. Once all 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 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 leads to an actual Pareto improvement. If a sustainable substitute for natural capital does not exist, the default value for depletion would be infinite and the resource could only be used sustainably. A renewable resource, such as a forest would be priced according to its sustainable yield. 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. The extinction of a species would carry an infinite cost since it's future value is unknown. 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 a very potent cancer fighting drug. 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.

3 The Inter-generational Problem

Section 2 has illuminated several market failures and systematic biases against inter-temporally
efficient valuation of natural capital. Even more serious concerns about the conventional approach to evaluation of natural capital depletion follow from the consideration of the inter-generational problem: the depletion of natural capital leads to benefits in the present and costs in the future, however, most of the costs are imposed on future generations who have no opportunity to influence decision making in the present. Conventional project analysis implies the use of a universal discount rate for all costs and benefits and, therefore, leads to a short-term focus that ignores inter-generational justice issues. This short-term focus may be justified for many short-lived production projects. However, it disregards the possible long-term welfare impacts of projects that are depleting natural capital. These inter-generational welfare impacts are at the core of the depletion problem. This section cannot comprehensively deal with the complex philosophical questions involved in inter-generational choice [see Berry (1983) for a discussion of some of these issues]. However, some important concerns of relevance to the evaluation of natural capital depletion will be presented. First, I will analyze the inter-generational resource distribution problem under the assumption that present individuals do not care at all about the well-being of future generations. Then, I will show that even if the current generation cares about future generations' well-being as much as about their own, a public good problem will prevent an efficient solution to the inter-generational problem unless the current generation makes collective provisions for future generations. Finally, a set of intuitive requirements for the evaluation of natural capital depletion is suggested in response to the inter-generational problem.

### 3.1 Inter-generational Justice

In this section, it is assumed that individuals do not consider the impacts of their decision making on the welfare of future generations. However, since decisions of the current generation about depletion of natural capital impact on the welfare of future generations, the latter have an interest in the decisions made by earlier generations that needs to be considered in some way. If the interests of all generations have to be taken into consideration, the concentration of economic analysis on efficiency is not justifiable since analysis of efficiency requires the assumption that the initial distribution of resources is the desired one. Concentration of economic analysis on efficiency may be justified for intra-generational choice because of the existence of more or less effective mechanisms to bring about the socially desired income distribution through government transfer payments. In inter-generational 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 criterium could, therefore, not prevent any single generation from consuming all resources of the earth leaving future generations uncompensated. Hence, inter-generational justice needs to be explicitly considered.

Use of a very low social discount rate has been proposed to address the problems of inter-generational justice. However, the choice of the discount rate for the depletion of natural capital does not lead to unambiguous results. While a lower rate increases the user costs and hence slows down depletion, the same low discount rate leads to increasing development of resources and hence increased demand and supply of the resource. In particular, a low discount rate increases exploration activities since the expected benefits from exploration weigh more against the exploration costs. Applying different discount rates to different projects would create problems of identification and possible inefficiencies. There are also conceptual concerns about modifying the discount rate. Norgaard and Howarth (1991) show in an overlapping generations model that the discount rate implied in the competitive equilibrium of trade between generations depends on the transfers
previous generations make to the following generations. The result is equivalent to the impact of changing income distribution in a one period model which, in general, would result in equilibrium price changes. Since the discount rate depends on how many resources the present generation distributes to future generations, the same discount rate should not be used to independently determine how many resources are to be allocated to the future (for example by use of the Hotelling rule). Hence, the distributional problem has to be solved before an appropriate inter-generational discount rate can be found. Directly adjusting the social discount rate for conservationist objectives is not appropriate.

The inter-generational justice dimension of natural capital depletion is best explained by considering the question, which generation owns the stock of a specific natural resource. Howarth and Norgaard (1990) have shown in a general-equilibrium model with two overlapping generations that for every possible distribution of resource ownership, there is a different efficient depletion path. An increase in the share of the resource owned by the first generation unambiguously reduces welfare of the second generation and vice versa. Hence, a self-interested early generation would assume ownership of the full resource stock, leading to gloomy welfare levels for future generations even though the resource is depleted efficiently. Von Amsberg (1992a) shows in a similar model for more than two generations that the efficient resource price would, in general, depend on the assumption which generation owns the resource. If the current generation assumes ownership of the full resource stock, future generations would be effectively excluded from bidding on the resource. Since non-adjacent generations cannot trade with each other directly, only a small channel, limited by the wealth of intermediate generations, would exist for all future generations to purchase parts of the resource stock from the early generation that assumes ownership of the resource stock.

While these overlapping-generations models are too simplistic to predict doom for future generations in the real world, they clearly show that efficient markets are not sufficient to ensure a minimum welfare level for future generations. They also show that current resource prices reflect implicit assumptions about which generation owns the resource and would change if the inter-generational welfare criterion is changed. This result corresponds to the useful separation of equity and efficiency issues in standard economic theory. An efficient market equilibrium can only be determined given a certain distribution of initial resources. In inter-generational choice, the same is true. In conventional welfare economics, little effort has been extended on defining the desired inter-generational distribution of resources. However, without agreement on such desired distribution of resources between generations, no statement can be made about the effectiveness of the market to bring about prices for natural capital that are consistent with inter-generational justice. The increased interest in the concept of sustainability can be viewed as an attempt to deal with this significant omission.

One possible approach for assessing the conflicting interests of different generations would be a Rawlsian "veil of ignorance" behind which all generations would have to agree on a social arrangement for inter-generational resource distribution, all without knowing which generation they are actually going to be [see Rawls (1971)]. The decision on the desired inter-generational welfare distribution can be expressed in an inter-generational social welfare function that reflects the desired ethical position (utilitarian, maxi-min or other forms). From the social welfare function, the optimal distribution of resources to different generations could be derived. However, a social welfare function is hardly operational in an inter-generational 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 would be Page's (1983) suggestion to require equal opportunities for every generation rather than a specified level of welfare.

Even if the market prices for natural resources reflected the optimal resource distribution, this would not take care of the inter-generational effect of externalities. Externalities would systematically discriminate against future generations and, hence, pose not only an efficiency but also an equity problem. Earlier generations would have an incentive to shift part of the costs of their activities as external costs into the future while future generations cannot burden earlier generations in a corresponding way. In the inter-generational context, the externality problem is aggravated by the fact that the potentially damaged individuals are not integrated into the institutional political process and, hence, would be neglected in the political processes that could remedy the externality problem.

3.2 Caring for Future Generations as Public Good

The preceding section has shown that efficient markets alone do not ensure a minimum welfare level for future generations if individuals are assumed to be indifferent toward the interests of future generations. This leaves open the question whether inter-generational altruism could solve the inter-generational justice problem. After all, very significant values are bequeathed to individuals of a new generation every day. The amounts involved are too large to be explained by uncertainty about a person's time of death alone. Hence, inter-generational altruism seems to be a reality. To analyze the impacts of inter-generational altruism, I will assume that current individuals are periodically replaced by individuals of a new generation, that the population size is stable, and that every individual cares about the welfare of her/his descendants as much as about her/his own welfare.

An efficiency problem arises because of the public-good nature of caring for future individuals [see 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 the first generation 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 grand-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 are difficult to conceive of 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 prevalent if individuals in the current generation cared not only about their individual descendants but also about the well-being of future generations in general [see Marglin (1963)]. Again, individuals would inefficiently under-provide resources for future generations. Social institutions that have traditionally served to alleviate this collective action problem have been rendered ineffective through cultural change. Such social institutions include the concept of responsibility toward the "seventh generation" in North American native ethics or European tradition according to which all family property was passed on to the oldest son instead of being divided between siblings. The latter 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. In summary, whether current individuals care about the well-being of their individual descendants or future generations in general, markets will bring about an allocation of resources to future generations that is inefficiently low from the viewpoint of the current generation’s preferences. Hence, inter-generational altruism may alleviate but does not solve the inter-generational problem.

3.3 Just Distribution of Resources between Generations

This section addresses the question what assumptions should be made about which generation owns natural capital in face of real-life uncertainties. Before that, however, an important issue needs to be clarified that can lead to confusion when the impact of choices about resource distribution on project evaluation are analyzed [see Page (1983) who raised this point]. In cost-benefit analysis, efficiency is commonly used in the sense of the potential Pareto criterium (also Kaldor or compensation criterium). This 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 criterium 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.

In inter-generational choice, the conditions that would justify use of the potential Pareto criterium 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. nuclear accident) on decision making. There is no reason to assume that the income distribution between present and future generations is explicitly endorsed. There is a systematic bias against future generations since politicians responsible for evaluation in the present are elected by present and not future generations. A systematic bias in favor of activities generating current benefits and future costs is the result. Furthermore, the decision not to compensate losers can be reversed within the same generation. In inter-generational choice, however, gainers will have died by the time losers live. Hence, the decision to not actually compensate is irreversible. For these reasons, efficiency should be confined to the actual and not the potential Pareto criterium in an inter-generational context. While gains and losses within each generation may still be added, the gains and losses accruing to different generations need to be considered explicitly and actual compensation of losing generations needs to be made. Then, no generation would lose from an activity. Applied to the example of ground water depletion, potential Pareto efficiency would allow earlier generations to deplete all ground water for the irrigation of export crops and to consume the full benefits from the export earnings while future generations would be left starving for sufficient drinking water. Future generations would derive little satisfaction from knowing that the project would have made them better-off compared to a without-project scenario if the previous generation had actually compensated them for the depletion of ground water.

The potential Pareto criterium provides important information that should not be ignored, even in an inter-generational context. If there exists an activity that implies a potential Pareto improvement, the status quo cannot be Pareto efficient since the activity in question plus compensation would be Pareto superior to the status quo. Efficiency requires that such an activity
and compensation be implemented. If present benefits outweigh future costs discounted at the marginal rate of return on investment, we know that the present generation could compensate future generations through investment that would lead to an actual Pareto improvement. Since present consumption at the cost of future generations cannot be justified without actual compensation, depleting resources for consumption cannot be based on discounting the opportunity costs of future generations. For example, considering the large amount of oil used by the present generation for purely consumptive purposes, significant long-term investments would be required to compensate future generations. It is difficult to calculate the compensating investment which would be required in addition to general investment undertaken in the economy. Currently, however, investment is generally not undertaken to compensate future generations and often is not suitable for that purpose. While industrial investment undertaken today may compensate the next generation, it seems to generate very little compensation for several generations ahead who will be burdened with the costs of present consumption.

The discussion of inter-generational equilibrium models has shown that the assumption of ownership of all natural capital by the first generation is unacceptable since it ignores the interests of future generations. Since agreement on an inter-generational social welfare function would be difficult to obtain, and even if agreement was obtained its operationalization would prove extremely cumbersome, at least some simple rules should be used which every generation could agree upon as a guideline for an acceptable inter-generational resource distribution. 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, adequate 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 paper. 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. It would not be sufficient to require compensation that leaves future generations as well off as without natural capital depletion since such arrangement would represent an undue advantage for early generations. Second, a later generation 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.

Under these guidelines for inter-generational 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 inter-generational justice reasons. Owning land would only include the right to harvest the sustainable yield of the land while leaving the capital value intact. Owning a mine would imply the right to exploit the resource only if adequate compensation of future generations was provided. Land ownership would become comparable to trusteeship rather than to ownership of human-made capital.
The guidelines for inter-generational resource distribution could be implemented through a sustainability constraint. In fact, consensus appears to be emerging that a sustainability constraint on current economic activities is the preferable approach to addressing the inter-generational problem [see Markandya and Pearce (1988) p.42 ff.]. The purpose of the sustainability constraint is to ensure some minimum level of welfare of future generations and a guarantee that a basic stock of natural capital is passed on to the next generation. 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. Inter-generational justice considerations would be reflected in the initial endowments assigned to each generation through the sustainability constraint. The sustainability constraint would lead to different equilibrium prices that would be not only efficient but also acceptable in view of inter-generational justice considerations.
Part B: **Sustainability and Project Evaluation**

Part A has demonstrated the deficiencies of conventional analysis of natural capital depletion. Two main conclusions followed from this discussion. First, due to the inherent incompleteness of conventional evaluation, the default assumption of natural capital as a free good must be reversed, and natural capital depletion costs should be equated to the cost of a sustainable substitute unless it can be shown with reasonable confidence that the true economic costs are less. Second, concerns about inter-generational justice require compensation of future generations for the depletion of natural capital and equal sharing of the benefits derived from it. In Part B, a more specific sustainability constraint will be developed which reflects these requirements and which approaches the question of appropriate substitutes for natural capital. Subsequently, a sustainability rule for evaluating natural resource depletion for practical analysis purposes will be derived from this sustainability constraint.

4 **The Appropriate Sustainability Constraints**

Sustainability is becoming an almost universally accepted policy objective. However, there is little agreement on the precise meaning of sustainability. Therefore, the discussion of different sustainability definitions, such as in Pezzey (1989), is useful. The purpose of a sustainability constraint is to restrict current economic activities in such a way that a specified variable, such as consumption or utility, can be maintained at its current value in perpetuity. Various definitions of sustainability differ in the variables which they constrain. The controversy between proponents of different sustainability constraints is based on different assumptions about the nature of substitutability between different assets. For example, Daly and Cobb (1989) discuss the distinction between strong and weak sustainability. A weak sustainability constraint only requires that the sum of the values of natural and human-made capital stock 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. The next section discusses the differences between strong and weak sustainability in detail. Subsequently, the appropriate geographic scope of a sustainability constraint is analyzed.

4.1 **Strong and Weak Sustainability**

The different sustainability constraints can be explained with the diagram in Figure 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 1. Questioning the assumptions about substitutability between different consumption streams, the next stronger utility 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 through a production process that combines
The four types of sustainability constraints are representative steps along the continuum between the abstract concept of human welfare and the physical concept of individual resources 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. The weak constraint, on the other hand, allows for a variety of substitution possibilities and only requires maintaining the welfare stream 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 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 is just barely met. 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 the "Hartwick-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 inter-generational world, the price path would have to be administered such that the resource is depleted efficiently under such constraint [see von Amsberg (1992)]. There would be no restriction on the type of compensating investment.

Under complete 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 regeneration capacity of the atmosphere. Considering non-quantifiable uncertainty such as the possibility of drastic technological advances, cultural changes or catastrophic events, providing a sensible distribution function for long-term prices would seem impossible.

In the absence of any reasonable estimate 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 equal 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 becomes very valuable, 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 such general investment as compensation would lead to a very 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 the Hartwick rule to ensure adequacy of the compensation with the desired
likelihood. Moreover, the concept of welfare is non-operational. As a result, a weak sustainability constraint is non-operational under uncertainty. It appears completely 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 inter-generational justice under real life uncertainties.

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 1). These consumption streams are the services derived from depletion of natural capital, such as heat, transportation, nutrition etc.. 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 stabilization, 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. If natural capital is necessary but not essential for production (output without natural capital would be zero but substitutability between natural and reproducible capital is sufficient to support a strictly positive output level into infinity from a finite stock of natural capital), specific investment that leads to sustainability of the consumption stream would be acceptable as compensation. Specific investment would 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 alter production functions in an unexpected way. 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 1). This constraint would allow the use of natural capital only if the supply streams entering production can be 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 stabilization, 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 are possible.
Finally, the strongest sustainability constraint would separately require sustainability of extraction from all different types of natural capital (level 4 in Figure 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, i.e. relocation of a cultivated forest. This sustainability constraint would eliminate the uncertainties, except for uncertainty about the size of stocks, harvest and sustainable yields and would be very operational. However, it would drastically restrict choices and ignores the existence of some 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 the strongest sustainability for bio-diversity 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 into infinity. By restricting compensation to functional substitutes, the problem of aggregation weights would be alleviated, since comparison can be made in physical units, such as energy content.

The stronger sustainability constraints reflect the intuition that future generations can be more adequately compensated through functional substitutes. The stronger sustainability constraints provide a built-in insurance for future costs of current economic activities. Since the price of functional substitutes is highly correlated, the value of the compensation is high whenever the value of the depleted resource is high and vice versa. The stronger sustainability constraint, therefore, ensures adequate compensation with a high degree of robustness. As a result, compensation through functional substitutes is the cheapest 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 behavior in view of the experience that technology and increasing knowledge can in fact significantly decrease the opportunities of future generations [see Daly and Cobb (1989), p.198 f.].

The choice between the four sustainability constraints in a particular instance involves considerable judgement and should depend on the degree of risk aversion, the nature and degree of uncertainty about the adequacy of inter-generational 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 generations 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 inter-generational 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.

4.2 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, zero net carbon dioxide emissions could be required on a global scale. Alternatively such constraint could be imposed for all countries separately. Even stronger, every city or every project could be required to achieve zero net carbon dioxide emissions. This decision depends on the substitutability between natural capital at different locations. The atmosphere is a global resource, and carbon dioxide emission reductions at any place in the world 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 coordination. Therefore, in the absence of global sustainability constraints, individual countries should 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. International lending agencies could play an important role in supporting national sustainability constraints even for global public resources, where individual countries would face a Prisoners' Dilemma situation. Similarly, if there was not already a sustainability constraint implemented at the national level, it should be imposed at a local or even project level. This process would lead to "bottom up" 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.
Shadow Prices Under a Sustainability Constraint

There is no convincing reason why an individual project needs to be sustainable if all costs are properly included in the analysis and if no costs are imposed on future generations. It is perfectly acceptable to undertake a project that generates positive net benefits over a finite lifetime. However, the determination of costs of a project that involves 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 Part A of this paper. 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. In practice this means applying the principles derived in Part A to the specific circumstances of the given project: 1) in the absence of reliable information on opportunity costs, the default value for depletion of natural capital would be the price of a sustainable substitute in order to overcome the inherent incompleteness of conventional evaluation; 2) benefits derived from the depletion of natural capital would be shared equally with all future generations in order to be inter-generational equitable; and 3) compensation to future generations would be provided through investment in sustainable substitutes in order to reduce uncertainty about the adequacy of the compensation, avoid wasteful resource use and ensure that compensation is sufficient for yet-unknown future high value uses of depleted natural capital.

5.1 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 inter-generational compensation for depletion of natural capital. The sustainable supply rule is an application of the three theoretical requirements discussed in the previous paragraph. The sustainable supply rule combines elements of Pearce's [Barbier, Markandya and Pearce (1988), 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 to adjust 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 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).

---

6 The differences between El Serafy's approach and the sustainable supply rule are discussed in Appendix B.
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 the resource. 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 steady income component which is generated through compensatory investment.

The demand curve for a service that can be provided by a non-renewable resource or its sustainable substitute is shown in Figure 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 would be \( C_r \). This is shown through the horizontal supply curve at \( C_r \). The line ABCD represents the demand (or marginal benefit) curve. At the price \( P_r \), no sustainable substitutes would be offered and demand would have to be satisfied with the non-renewable resource. Market demand at price \( P_r \) 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 equaling 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 is equal for all generations.

Compensating investment into the sustainable substitute would, in time, reduce the unit cost of the sustainable substitute from its current level \( C_r \). 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 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 forever; 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.

Appendix A shows the calculation of the sustainable price for the simplest case of a non-renewable resource with zero extraction costs and a perfect sustainable substitute. For the quantity
of the resource, \( M \), extracted per period the sustainable price, \( P_s \), would have to be set such that  
\[ P_s \cdot M \]  
(invested in every period until depletion of the non-renewable resource, would generate a return of  
\[ (C - P_s) \cdot M \]  
in every period after depletion. This results in the following equation for the sustainable price derived in Appendix A:

\[
P_s = e^{-\frac{r}{R}} C_s
\]  

(1)

where \( r \) is the return on investment in sustainable substitutes, \( R \) is the total stock of the non-renewable resource and \( R/M \) 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 stability of the sustainable price. The quantity \( M \) of the resource will be available at the price \( P_s \) before depletion from the non-renewable resource and thereafter from the sustainable substitute.

If the extraction rate of the non-renewable resource, \( M \), 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 (1) 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 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 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 valuation of the input to a resource extraction project or 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 used) would be required for the project to be acceptable.

Equation (1) is based on highly simplistic assumptions and probably 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 (1) (see Appendix A). 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.

Figure 3 compares the price paths resulting from use of the sustainable supply rule and conventional depletion according to the Hotelling path. 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 interest rate with the initial price set such that depletion occurs exactly when the price reaches $C_s$ as shown in Figure 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 the 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 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 traditional 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 welfare transfer mechanisms between generations. The defense of the sustainability 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 traditional 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 inter-generational welfare transfer mechanisms were in place.

5.2 Application of the Sustainable Supply Rule

In this section, the sustainable supply rule will be illustrated by means of several examples. Consider first the previous example of ground-water depletion. A sustainable supply curve for water can be found by estimating the cost of compensating investment in a water desalination plant run by solar energy. Again, I assume zero extraction cost for ground water and $C_s$ as the present unit cost of producing desalinized seawater at any desired quantity. 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 annually 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 (1) with the current depletion rate $M$, total stock left in the ground, $R$, 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. Subsequently, the NPV of the project could be calculated and the project and the compensating investment implemented in case of a positive NPV.

For pricing 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 would likely be 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 will be 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 the equation for the sustainable price with non-zero extraction costs derived in Appendix B. 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 per end-use energy unit or per energy service unit 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 conceive of 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 afforestation 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.

Similarly, 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 the natural capital intact. Hence, a new project which would increase the atmospheric carbon dioxide concentration would have to bear the costs of investment, for example in afforestation, 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 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.

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 (1) was derived, refers to a situation in which facilities for the sustainable production of the substitute already exist. Then, compensating investment doesn't 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 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 production facilities for a sustainable substitute themselves. Only after such investment is sufficient to produce the desired quantity of the substitute, further investment should be made into general sustainable production to subsidize the cost of the sustainable substitute. In any case, would be the real rate of return on the actual compensating investment undertaken. If the sustainable substitute is a biological resource, the natural growth rate of the resource would be the appropriate rate for r.

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 eased for this purpose since the relevant rate r is the rate of return on R&D measured at the fixed output price . 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 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 .

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 be evaluated, following conventional analysis, 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. 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 and should be implemented if it was the least cost alternative for achieving sustainability.
Part C: Sustainability and Project Evaluation: Case Studies

The purpose of Part C of this paper is to analyze several recently appraised World Bank projects. Following the discussion of several recurrent issues in these case studies, several detailed case studies are presented in which the application of the sustainable supply rule to the economic analysis of these projects is demonstrated. The following summary of the treatment of natural capital depletion in the economic analysis of several other World Bank projects illustrates some of the deficiencies of conventional analysis as discussed in Part A of this paper.

Some issues re-appear in the analysis of several Bank reports examined for the following case studies. One of these issues is the treatment of natural capital as a free good. Many projects use natural capital as an input but do not include a corresponding user cost in the economic analysis. For some of these projects, an extremely high economic rate of return of 50% or even 70% already indicates that the depletion of natural capital is not properly accounted for. In most projects that involve depletion of a natural resource, such as mining or oil/gas development projects, no user cost or depletion premium is included in the calculation of economic project costs. 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. While, in many cases, it may turn out that the depletion premium for the extraction of a natural resource is small, it should, nevertheless, always be explicitly considered. In the case studies, the sustainable supply rule is used to determine an appropriate depletion premium.

In many 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. Under a sustainability constraint this assumption would be unacceptable in most instances. The lack of observable commercial uses would be insufficient for the assumption of zero opportunity cost of land, especially if the project does not only use but also degrade the land. Most land serves many functions beyond their obvious commercial use, including use for various subsistence activities and recreation. In an increasingly crowded world, remaining wilderness areas are important for preserving biological diversity. 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. The approach used to determine the land value in the absence of apparent commercial uses or a reliable market price is to consider the replacement costs. 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.

Atmospheric emissions are usually not evaluated in the economic analysis of Bank projects even though possible damage from emissions, i.e. of sulphur dioxide, 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 discussed but can 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; however, a damage cost of zero is usually not the best estimate available. The expected damage costs for most pollutants, however, would be strictly greater than zero and an explicit evaluation of expected damages is preferable even under significant uncertainty. Consider in comparison that future commodity prices are highly uncertain, however, the future output of a production project would never be evaluated at a price of zero. Similarly, the expected costs of damage from emissions should be estimated and included in the analysis accompanied by sensitivity analysis for different damage cost estimates. 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. Second, many projects include pollution abatement technology, and the report states that the remaining emissions do not exceed international emission standards. 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.

So far, resource depletion, land use and emissions resulting directly from the project were considered. Another category of projects produces 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 or institutional arrangements such as the Global Environment Facility (GEF) would be appropriate to facilitate the required transfer payments. In any event, international lending institutions should not support a project that is desirable only from a national perspective but is undesirable from a global perspective.

There is also a wide range of projects that do not deplete but restore or enhance natural
capital. These projects, i.e., reforestation projects or projects increasing the efficiency of natural resource use, are usually justified by enumerating the observable benefits from the investment. Because of the pervasive nature of benefits generated by natural capital, this leads to a systematic underestimation of the economic benefits from the project. In a situation in which natural capital is being depleted, a project that restores natural capital or compensates for depletion should be evaluated by a cost effectiveness study, comparing it to alternative projects that would achieve the same end. 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. This approach would appropriately reflect the prevailing uncertainty about the pervasive benefits from a restoration project. As a result, the implementation of a sustainability constraint would not necessarily reduce the number of desirable projects. It would merely suggest a shift in Bank lending from depletion projects to projects that invest in natural capital or increase the efficiency of its use.

It was not attempted to analyze all Bank reports that deal with Bank supported unsustainable activities. While the selected report are not necessarily representative, all reports that were analyzed are also mentioned in this paper, and the discussed reports are not deliberately selected as examples for inappropriate treatment of natural capital depletion. The analyzed reports are summarized in Table 1. The case studies are based on the Staff Appraisal Report (SAR) of the respective project and relevant background papers for the economic analysis when those were available. Prices, exchange rates and cost estimates were used as given in the SAR and reflect the price levels at the time of project appraisal. Costs and other data that are not explicitly referenced, are taken from the SAR or background papers of the project.

6 Detailed Case Studies

The purpose of the following case studies is to show the feasibility of reflecting a sustainability constraint in the economic analysis of projects. Hence, the focus is on methodology and not on the precision of individual cost estimates. 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. Shadow prices (for example shadow wage rates) usually evolve from many years of work in a given country. The commodity price forecasts used in project analysis are provided by a team of World Bank specialists [see World Bank (1991)]. Similarly, the calculation of shadow prices for natural capital depletion is a complex task. These case studies show that reasonable shadow prices can be calculated with very moderate effort. If the Bank, however, decides to use sustainability prices in the evaluation of its projects, comprehensive guidelines should be compiled and made available to operations divisions, similar to those already provided for world commodity price forecasts. Such guidelines should be based on all available knowledge including the history of reserve estimates.

The sustainability prices used in the case studies 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. Even if the marginal rate of return in the respective economy was 10-12%, it would be unrealistic to expect that large-scale compensatory investment could be made at this rate. Furthermore, as the worldwide integration of national financial markets progresses, it would be expected that the rate of return on investment
Economic Analysis:
D - Depletion Premium: - ignored, + included, ? incomplete
L - Opportunity cost of land: - assumed to be zero, + included
E - Emissions: - ignored or incomplete, + included

Table 1 Summary of Analyzed Bank Reports

would converge to the rates obtained on international markets. Hence, a discount rate of 7%, a midpoint estimate between the real rate of return on international financial markets and the opportunity cost of capital, has been selected for the base case calculations. Sustainability premia are also calculated for rates of return of 5% and 10%.

6.1 Nigeria: Oso Condensate Field Development Project
(February 10, 1991, SAR 8245-UNI)

The Project
The Oso Condensate Field Development Project consists of the commercial development of an off-shore condensate field that is jointly owned by Nigeria's national petroleum company and Mobil Producing Nigeria. Condensate is equivalent to very light crude oil. The main project objective is the increase of Nigeria's hydrocarbon exports. The recoverable reserves of the field are estimated at 330 million barrels and would be extracted over the 21-year lifetime of the project. The Oso field comprises about 1.5% of Nigeria's oil reserves. Total oil reserves of the country are about 22 billion barrels including estimated undiscovered reserves. At the current country-wide extraction rate of 1.6 million barrel per day this implies a remaining lifetime of the oil reserves of approximately 38 years. The stated rationale for World Bank involvement in the project is that external financing for the development of the condensate field would be difficult to obtain without World Bank participation. The project was appraised by the World Bank/IFC with an economic rate of return of 51%.

The economic analysis does not include any user cost or depletion premium. Hence, the economic rate of return reflects the full resource rent without considering the opportunity costs of depletion. The discussion of oil prices in the SAR focuses on the risk of an oil price decline that would reduce the project's rate of return. No consideration is given to the risk of oil price increases that could reduce the economic value of the project due to the increased opportunity costs of depletion. The World Bank oil price projections that were used for the calculation of the economic rate of return are flat for the lifetime of the project (around $22/bbl in constant 1990-$.). Since oil prices are not expected to rise at or above a rate equalling the assumed opportunity cost of capital, the use of an opportunity cost for depletion, based on these price projections, would not have led to the rejection of the project.

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, its combustion leads to accumulation of carbon dioxide in the atmosphere. Therefore, according to the sustainable supply rule, depletion needs to be evaluated at the sustainable price derived from the cost of a sustainable substitute. Since condensate is primarily used as an energy commodity, substitution of condensate with another storable form of energy would be acceptable under a sustainability constraint. Other hydrocarbons, such as gas evaluated at its energy content, would be almost perfect substitutes for condensate. 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.

There are several renewable energy sources that are almost perfect substitutes for condensate. 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. Since it is based on solar energy, 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 in Nigeria seems to be feasible due
to 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.

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 at dark 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 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.

**Calculation of Sustainable Prices**

The sustainable price for the depletion of condensate 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. In order to separate the different issues entering the calculation, the sustainable price will be calculated in the following steps: a) sustainable price for the Oso condensate field; b) sustainable price for Nigeria's oil reserves; c) sustainable price for Nigeria's oil and gas reserves; d) sustainable price taking the expected growth in energy demand into account; e) sustainable price considering efficiency gains in energy use; f) sustainable price considering restrictions on acceptable carbon dioxide emissions.

**a. The Sustainable Price of Depletion of the Oso Field**

According to the production plan, 330 million barrels are to be extracted from the Oso field over 21 years. Peak production will be reached in year two with production declining after year four. If a sustainability constraint was imposed on this project, the average production over the project's lifetime of 15.6 million barrels of condensate per year would have to be replaced by production of an equivalent amount of solar hydrogen after year 21. 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 condensate is $90 (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" [see Anderson and Bird (1992), p.16]. The extraction costs for condensate from the Oso field are $4.4 per barrel ($2.4/bbl development costs and $2/bbl recurrent costs).

The sustainable price is the price that, if paid in perpetuity for every barrel of oil or the equivalent of its sustainable substitute, will cover the costs of oil depletion as well as subsequent production of solar hydrogen. The sustainable price is found by equating the present value of the
costs of extracting oil and producing solar hydrogen with the present value of the revenue stream obtained for the sale of the equivalent of 15.6 million barrels per year in perpetuity. Let \( R \) be the present value of the infinite revenue stream resulting from a sustainable price \( P \), for one barrel of oil equivalent:

\[
R = \int_0^{21} e^{-rt} x_t P \, dt + \int_{21}^{\infty} e^{-rt} 15.6 \times 10^6 \, dt \quad (2)
\]

where \( x_t \) is the actual extraction rate during the lifetime of the project \( (x_1 = \{18.3, 36.5, 36.5, 36.5, 33.5, 30.1, 26.1, 21.7, 17.9, 14.7, 12.2, 10.1, 8.2, 6.6, 5.3, 4.3, 3.3, 2.5, 1.9, 1.4, 0.9\} \) in million bbl/a), and \( r \) is the assumed (continuous time) rate of return on compensatory investment. Let \( C \) be the present value of the costs of extracting oil and producing the sustainable substitute:

\[
C = \int_0^{21} e^{-rt} x_t 4.4 \, dt + \int_{21}^{\infty} e^{-rt} 15.6 \times 10^6 \times 90 \, dt \quad (3)
\]

Setting \( R = C \) and solving for \( P \), at a seven percent rate of return, the sustainable price is $21.8/bbl. Hence, the depletion premium (sustainable price minus extraction costs) is $17.4/bbl. This means if $17.4 were invested per barrel extracted at a real rate of return of 7%, this investment would be sufficient to replace the depleted Oso field by production of solar hydrogen to be sold at $21.8 per barrel equivalent. The funds could be invested in the capital markets until the time at which physical investment in solar hydrogen production facilities would be required in order to replace the oil reserves at the time of depletion.

b) The Sustainable Price of Depletion for Nigeria's Total Oil Reserves

Nigeria has many other, yet undeveloped, oil reserves. Since other oil reserves are perfect substitutes for the depleted Oso field, those other oil reserves can be depleted before energy supply has to be converted to solar hydrogen as the sustainable substitute. Therefore, a uniform sustainable price for the depletion of all of Nigeria's oil reserves can be calculated and should be used instead of different sustainability premia for the depletion of each individual oil field. Nigeria's 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. Hence, the energy equivalent of 584 million barrels of oil per year would have to be provided through solar hydrogen after year 38. Assuming $4.4/bbl as the extraction costs for all of Nigeria's oil reserves, the sustainable price can be calculated as above:
Setting \( R = C \), the sustainable price is $11.1/bbl. The depletion premium is $6.7/bbl.

c) **The Sustainable Price of Depletion for Nigeria's Total Oil and Gas Reserves**

Nigeria 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 considered for all of Nigeria's gas and oil reserves. Using the total oil and gas reserves equivalent to 49 billion barrel oil and current extraction of oil and gas equivalent to 612 million barrel per year, the lifetime of oil and gas reserves together would be 80 years. Hence, solar hydrogen would not need to be produced until the year 81. Again, making the assumption of constant and equal extraction costs for gas and oil, costs and revenues can be calculated:

\[
R = \int_0^{37.7} e^{-rt}584 \times 10^6 P_e dt
\]

\[
C = \int_0^{37.7} e^{-rt}584 \times 10^6 \times 4.4 dt + \int_0^{37.7} e^{-rt}584 \times 10^6 \times 90 dt
\]

The sustainable price would be $4.8/bbl and the depletion premium $0.4/bbl. The effect of compensatory investment accumulating returns over 80 years would, thus, reduce the depletion premium drastically compared to a scenario without gas.

d) **The Sustainable Price With Increasing Energy Demand**

The worldwide 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. Since the possibility to increase energy use efficiency will be analyzed in the following section, the calculations in this section are based on an equivalent increase in primary energy use. If extraction of gas and oil from Nigeria's reserve was rising at 3.7% per annum, depletion would occur not after 80 but after
37.5 years. It is assumed that energy demand would remain constant after year 38 and solar hydrogen equivalent to oil and gas extraction in year 37 would have to be provided at the sustainable price in perpetuity. Based on these assumptions, the present value of costs and revenues are calculated:

\[
R = \int_0^{37.5} e^{(0.036-r)t} 612 \times 10^6 P_s dt + \int_{37.5}^{\infty} e^{0.036 \times 37.5 - rt} 612 \times 10^6 P_s dt
\]

\[
C = \int_0^{37.5} e^{(0.036-r)t} 612 \times 10^6 \times 4.4 dt + \int_{37.5}^{\infty} e^{0.036 \times 37.5 - rt} 612 \times 10^6 \times 90 dt
\]

Now, the sustainable price would be $19.1/bbl, equivalent to a depletion premium of $14.7/bbl. This calculation implies the assumption 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 population 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.

e) The Sustainable Price With Energy Efficiency Increases

Clearly, an increase in primary energy production, assumed in the previous section, is not the least cost option for satisfying the increasing demand for energy services. Substitution of capital for primary energy and investment in research and development can also satisfy part of the increasing demand for energy services. At this point, only rough cost estimates are provided that should be replaced with more precise calculations, as those estimates become available. The costs of increasing energy use efficiency are derived from Lovins' (1990) preliminary estimates of the full technical potential to save US oil consumption. If these estimates are considered optimistic, this would introduce a downward bias in the resulting sustainability premium. However, the cost estimates are based on already available technologies. Figure 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

\[
K = -3 - 10.4 \log \left( \frac{E+0.85}{0.85} \right)
\]

where \(K\) is the capital cost in $ per barrel of oil saved, and \(E\) is the share of current primary energy requirements for one unit of energy service. If \(S\) is the share of energy saved, shown on the horizontal axis in Figure 4, then \(S = 1 - E\).

It is clearly unrealistic to expect that any desired level of energy efficiency increase can be achieved immediately. It is estimated that annual increases in energy efficiency of 2% are possible over several decades [see Worldwatch Institute (1988), 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, Nigeria'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, $c_e$, is the integral of the cost function depicted in Figure 4 from zero to the achieved level of energy savings, which, as discussed above, is assumed to be a function of time:

$$
c_e = \int_0^{1-e^{-0.02t}} -3-10.4 \log \left[ \frac{0.85-S}{0.85} \right] dS = -0.026 + 7.42 (1-e^{-0.02t}) + 10.42 (e^{-0.02t} - 0.15) \log[1.003 - 1.18 (1-e^{-0.02t})]
$$

Now, the price of energy service - not necessarily the price of primary energy - should be made 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.

The sustainable price for the energy service from one barrel of oil today, resulting from $C_X + C_H + C_E = R$, would be $6.5/bbl and the depletion premium $2.1/bbl. Under the assumptions made, investments in energy efficiency would be far less costly than accommodation of demand increases.
by primary energy supply increases. If depletion of fossil fuels was the only concern with respect to the sustainability of the Oso project, $2.1/bbl would be the appropriate depletion premium to be used in evaluating the project.

f) The Sustainable Price with Restrictions on Carbon Dioxide Emissions

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 continuing 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. The following calculations are based on the assumption that global carbon dioxide emissions need to be cut in half by the year 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. The calculations are easily repeated for alternative carbon dioxide scenarios should new evidence surface that would suggest a different scenario.

The scenario under e) would imply significant increases in carbon dioxide emission from the energy produced in Nigeria over the next 50 years. Hence, an alternative scenario is developed under which extraction of Nigeria's oil and gas reserves is constrained by the requirement that carbon dioxide emissions from Nigeria's energy sources are gradually reduced to one half of 1990 levels between 2000 and 2050. Under this scenario shown in Figure 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 2 and Figure 6. Under this scenario, gas would be depleted after 85.7 years. Thereafter, it would be fully replaced by hydrogen. Now 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. Under the carbon dioxide reduction scenario, the sustainable price of one barrel of oil today would be $14.6/bbl (excluding extraction costs: $10.2/bbl).

The sustainable price of $14.6/bbl reflects the depletion of fossil fuel as well as the carbon dioxide constraint. To separate those two effects, a different scenario is calculated under which unlimited gas reserves are assumed. Hence, the extraction of gas could continue at the rate admissible under the carbon dioxide constraint even after the year 86. The resulting sustainability price is $14.5/bbl. Hence, the depletion premium under the carbon dioxide constraint would be only $0.1/bbl (the depletion 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 Oso field would be $10.1/bbl for unsustainable use of
Table 2 Carbon Dioxide Reduction Scenario

<table>
<thead>
<tr>
<th>Year</th>
<th>Total</th>
<th>Oil</th>
<th>Gas</th>
<th>Renew</th>
<th>CO₂ Emiss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in mio bbl</td>
<td>oil equivalent</td>
<td>mio t C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1989</td>
<td>640</td>
<td>612</td>
<td>28</td>
<td>0</td>
<td>83</td>
</tr>
<tr>
<td>1990</td>
<td>651</td>
<td>612</td>
<td>39</td>
<td>0</td>
<td>84</td>
</tr>
<tr>
<td>1991</td>
<td>662</td>
<td>612</td>
<td>50</td>
<td>0</td>
<td>85</td>
</tr>
<tr>
<td>1992</td>
<td>673</td>
<td>612</td>
<td>61</td>
<td>0</td>
<td>86</td>
</tr>
<tr>
<td>1993</td>
<td>685</td>
<td>612</td>
<td>73</td>
<td>0</td>
<td>87</td>
</tr>
<tr>
<td>1994</td>
<td>696</td>
<td>612</td>
<td>84</td>
<td>0</td>
<td>88</td>
</tr>
<tr>
<td>1995</td>
<td>708</td>
<td>612</td>
<td>96</td>
<td>0</td>
<td>89</td>
</tr>
<tr>
<td>1996</td>
<td>720</td>
<td>612</td>
<td>108</td>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td>1997</td>
<td>732</td>
<td>612</td>
<td>120</td>
<td>0</td>
<td>91</td>
</tr>
<tr>
<td>1998</td>
<td>745</td>
<td>612</td>
<td>133</td>
<td>0</td>
<td>92</td>
</tr>
<tr>
<td>1999</td>
<td>758</td>
<td>612</td>
<td>146</td>
<td>0</td>
<td>93</td>
</tr>
<tr>
<td>2000</td>
<td>770</td>
<td>600</td>
<td>151</td>
<td>19</td>
<td>92</td>
</tr>
<tr>
<td>2005</td>
<td>838</td>
<td>541</td>
<td>181</td>
<td>116</td>
<td>87</td>
</tr>
<tr>
<td>2010</td>
<td>912</td>
<td>482</td>
<td>210</td>
<td>220</td>
<td>82</td>
</tr>
<tr>
<td>2015</td>
<td>592</td>
<td>423</td>
<td>239</td>
<td>329</td>
<td>76</td>
</tr>
<tr>
<td>2020</td>
<td>1079</td>
<td>364</td>
<td>269</td>
<td>446</td>
<td>71</td>
</tr>
<tr>
<td>2025</td>
<td>1174</td>
<td>305</td>
<td>298</td>
<td>571</td>
<td>66</td>
</tr>
<tr>
<td>2030</td>
<td>1277</td>
<td>246</td>
<td>327</td>
<td>704</td>
<td>61</td>
</tr>
<tr>
<td>2035</td>
<td>1390</td>
<td>187</td>
<td>357</td>
<td>846</td>
<td>55</td>
</tr>
<tr>
<td>2040</td>
<td>1487</td>
<td>129</td>
<td>386</td>
<td>972</td>
<td>50</td>
</tr>
<tr>
<td>2045</td>
<td>1487</td>
<td>70</td>
<td>415</td>
<td>1002</td>
<td>45</td>
</tr>
<tr>
<td>2050</td>
<td>1487</td>
<td>11</td>
<td>445</td>
<td>1031</td>
<td>40</td>
</tr>
<tr>
<td>2055</td>
<td>1487</td>
<td>0</td>
<td>450</td>
<td>1037</td>
<td>39</td>
</tr>
<tr>
<td>2060</td>
<td>1487</td>
<td>0</td>
<td>450</td>
<td>1037</td>
<td>39</td>
</tr>
</tbody>
</table>

*Carbon emissions are calculated from Deutscher Bundestag (1989), p.489: 0.29 kg CO₂ per Kwh from oil; 0.19 kg CO₂ per Kwh from gas; mass of CO₂ is 3.67 times the mass of C.*

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 condensate output needs to be reduced by $10.1/bbl for unsustainable use while an economic cost of $0.1/bbl of input (condensate extraction) should be included. The equivalent sustainability premium per ton of carbon emissions would be about $77.

**Impacts on the Desirability of the Project**

Table 3 summarizes the calculated sustainability premia for the different approaches used and also shows sustainability premia for a 5% and 10% assumed rates of return. Approach f) represents the most comprehensive model including the substitution of condensate with solar hydrogen, efficiency increases in energy use and a constraint on admissible carbon dioxide emissions. With an assumed real rate of return on compensatory investment of 7%, the sustainability premium is $10.2/bbl of condensate extracted.

Table 4 shows the calculations for adjusting the projects 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
Table 3 Summary of Sustainability Premia for Oil Extraction in Nigeria

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 7. 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 an opportunity cost of depletion) of $1.72 billion, $1.25 billion would have to be invested as compensation for depletion of the condensate field and the atmosphere's absorption capacity for carbon dioxides.

Comments

Two complications arise from the point of view of national welfare maximization. Nigeria 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 implementation of such a decision. On the other hand, the required compensatory investment in sustainable substitute points toward a sensible strategy on how Nigeria can mitigate the negative consequences that global carbon dioxide emission limits would have for oil exporting countries. In particular, since Nigeria is geographically well positioned for investment in solar hydrogen, such investment is well suited to compensate for the loss in revenues that would result from restrictions on carbon dioxide emissions in those countries that now import Nigerian oil.

Second, Nigeria 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 petroleum consumption takes place). However, if all countries agreed on the use of a sustainability
constraint, this apparent problem would 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, Nigeria would obtain a higher price for sustainable condensate (for which compensatory investment has been undertaken) than for unsustainable condensate, 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 the World Bank and other international lending agencies to promote, and support through concessionary lending, global thinking and the application of a sustainability constraint even where it is not in the interest of narrowly defined national welfare maximization.

6.2 Malawi Second Wood Energy Project (February 26, 1986, SAR 5914-MAI)

The Project

The Second Wood Energy Project supports measures to reduce the gap between fuel wood
production and consumption in Malawi. The main components of the project are the establishment of fuel wood tree plantations (mainly eucalyptus) to increase fuel wood supply and the introduction of high-efficiency household stoves and charcoal kilns in order to increase efficiency of fuel wood use and contain demand. Currently, fuel wood consumption in Malawi is 8.6 million m³ per annum (rural households 59%, tea and tobacco estates 23%, urban households 12%, other industries 6%) while the mean annual increment in the country's accessible forests is only 4.6 million m³. If no counter-measures are taken, all accessible forests would be depleted in about 25 years at the current rate of consumption. At full development, the project would supply 230,000 m³ of fuel wood annually through plantations on 23,000 ha.

The economic analysis of the project does not include the benefits from increasing the efficiency of fuel wood use, since the corresponding project components are pilot activities. Only incremental fuel wood production is included in calculation of the project's economic benefits. In the base case, the fuel wood is evaluated in terms of reduced costs of transport and wood collection and sustained agricultural productivity due to reduced deforestation. The economic rate of return of the project is 10% in the base case. Alternatively, fuel wood production is evaluated in terms of charcoal and kerosene prices which yields a significantly higher ERR. However, evaluation of fuel wood in terms of high price substitutes is considered problematic since most consumers would not be able to afford these substitutes. Additional benefits from arresting deforestation are mentioned.
in the SAR’s discussion of the economic analysis; however they are not included in the numerical analysis. Evaluation of fuel wood produced in terms of avoided transportation leads to a critical dependency of the project’s desirability on the location of plantations. In fact, if plantations were established at the location of current deforestation, a major benefit component would disappear and the project would likely appear undesirable.

The Issues

Fuel wood use in Malawi is unsustainable in two ways. First, since forests are being depleted rapidly, the supply of fuel wood through deforestation is unsustainable. Second, natural forests provide a variety of benefits reaching from soil and climate stabilization to increased agricultural productivity. Eucalyptus plantations are a sustainable substitute for fuel wood supply from natural forests but are no substitute for the natural forest itself. Therefore, it is not sufficient to replace fuel wood from natural forests with a sustainable substitute once all forests are depleted. Deforestation itself is incompatible with sustainability, especially regarding the uncertainties involved in measuring the benefits from a standing natural forest. Therefore, under a sustainability constraint, fuel wood supply has to be made sustainable and deforestation has to be arrested. The project contributes to both objectives.

Under a sustainability constraint, implementing a project that remedies an unsustainable situation is like paying a bill and does not require an explicit economic justification. However, an economic analysis needs to confirm that the project is achieving sustainability at the least possible cost. Therefore, the question is not whether to stop deforestation but how to do so. The appropriate comparison for calculation of the incremental benefits from the project is, therefore, not between a with and without project scenario but between a scenario with this particular project and the best alternative scenario for achieving sustainability. Two calculations are made to confirm that the project is the least cost alternative for achieving sustainability. First, the project output is evaluated at the sustainable price of an alternative fuel that would have to be used as a substitute for unsustainable fuel wood use in the absence of the project. Second, it needs to be confirmed that the marginal benefits of fuel wood consumption exceed the marginal costs of sustainable fuel wood supply and that, therefore, the current level of fuel wood consumption should be sustained.

Valuation of Project Output in Terms of the Best Alternative for Achieving Sustainability

As an alternative evaluation of the fuel wood production under the project, the SAR contains an analysis of the value of fuel wood in terms of kerosene as a substitute. This approach is ultimately rejected in the SAR since most consumers would not be able to afford kerosene. However, this calculation can be used as the basis for evaluating wood output under a sustainability constraint. Replacement of unsustainable fuel wood consumption with kerosene is assumed to be the best alternative for achieving sustainability. Of course, kerosene consumption is not sustainable itself either. Therefore, the sustainability price of kerosene has to be used. Malawi is an oil importing country. The current cost of kerosene is determined by using world market prices for oil, which is assumed to be $20/bbl. The appropriate sustainability premium is obtained from a calculation like in Section f) of the case study on the Nigeria Oso Field Development Project, however, the extraction cost is replaced by the world market price of oil. The resulting sustainable price for oil is $23.5/bbl, equivalent to a sustainability premium of $3.5/bbl. (The sustainability premium of $3.5/bbl is based on an assumed real rate of return on compensatory investment of 7%. For 5% and 10%, the sustainability premium would be $5.1/bbl and $1.9/bbl respectively.) This implies that if $3.5
were invested for every barrel of oil imported by Malawi, energy could be provided from sustainable sources (including consideration of a carbon dioxide emission constraint) at a sustainable price of $23.5/BOE in perpetuity. Since this price is determined primarily by a carbon dioxide constraint that would apply globally, this premium, based on reserves in Nigeria, can be used as a good approximation for globally sustainable energy supply.

The sustainability premium for one barrel of oil with an energy content of 6 GJ is $3.5. Hence, the sustainability premium for one liter of kerosene with an energy content of 36 MJ would be $0.02, equivalent to MK 0.04. This increases the economic value of kerosene to MK 0.64/l and the value of fuel wood to MK 78/m³. Adjusted for transport and processing costs, the economic cost of forest depletion would be MK 63.2/m³. This compares to an original valuation of the avoided costs of deforestation of MK 22.8/m³. At a shadow price of fuelwood output of MK 70.5/m³, the ERR of the project would be approximately 28% (compared to 10% in the base case and 26% if output is evaluated at the economic value of kerosene without the sustainability premium).

Another approach for achieving sustainability would be the reduction of fuel wood consumption. The costs of this approach would be the foregone benefits of consumption and the costs of enforcing restrictions on unsustainable forest clearing. There are no estimates of enforcement costs available. However, the SAR clearly indicates that this task would be highly unrealistic and well beyond the institutional capabilities of the government. The urban fuel wood market price is MK 17/m³, compared to the marginal cost of producing fuel wood in plantations of MK 15.3/m³. This gives an indication that even if a ban on unsustainable fuel wood use could be implemented, it would imply a larger cost than achieving sustainability through forest plantation projects. Increasing energy use efficiency is an additional option for reducing unsustainable forest depletion. Pilot activities for increasing energy use efficiency are included with the project. Due to the small scale of the plantations under this project compared to the fuel wood gap, efficiency increases can be viewed as complementary to the analyzed plantations. Hence, the project is the least cost alternative for achieving sustainability and should be implemented.

**Calculation of the Sustainable Price of Fuel Wood**

In this section, the sustainable price of fuel wood supply will be calculated in order to determine the investment required to convert fuel wood consumption to a sustainable basis. It is assumed that sustainability requires conversion to sustainable fuel wood supply as soon as possible. Here, it is assumed that the fuel wood gap will be filled by fuel wood plantations only. The option of increasing fuel wood use efficiency should certainly be pursued as well but is not analyzed in this case study. The sustainable price of fuel wood in Malawi is the price at which fuel wood can be sustainably supplied at the current level of consumption in perpetuity. Hence, the sustainable price has to cover the cost of afforestation sufficient to create a forest that has the current consumption as its sustainable yield. Harvest in tree plantations will not begin until six years after project start. Therefore, the required area of tree plantations depends on the natural tree cover left in year 6.

The currently accessible forest covers approximately 3.8 million ha. One hectare of standing natural forests consists of 40 m³ wood. The mean annual increment (MAI) in natural forests is 1.2 m³/ha. This relation can be approximated by a growth rate of 3% per annum. At a growth rate of 3% and an annual harvest of 8.6 million m³, the current stock of 153 million m³ will be reduced to 126.2 million m³ in year 6. This is determined by solving a differential equation for the change in biomass, x:
\[ x_t = \log[1.03] x_t - 8.6 \times 10^6, \quad x_0 = 153 \times 10^6 \]
\[ x_t = 291 \times 10^6 - 138 \times 10^6 e^{0.029t} \quad (10) \]

This equation was also used to determine that the forest stock will be reduced to zero after 25 years if current depletion continues. The sustainable yield of the stock remaining in year 6 will be 3.8 million m\(^3\)/a. Hence a gap of 4.8 million m\(^3\) per annum has to be met from tree plantations after year 6. The MAI of one ha of tree plantation is assumed to be 12 m\(^3\). However, plantations are only harvested in years 6, 11, 16 and 21. At every harvest, the yield is assumed to be 60 m\(^3\)/ha. The plantation has to be reforested in year 21. If in each of the years 1 to 5 plantations covering 80,200 ha are established and then reforested after twenty years, respectively, the fuel wood gap can be filled in perpetuity (60 m\(^3\)/ha \times 80,200 ha fills the gap of 4.8 million m\(^3\)). The project comprises reforestation of about 23,000 ha. The extent of deforestation in Malawi becomes apparent if it is considered, that seventeen projects of equal size would have to be implemented over a five-year period to accommodate the transition to sustainable fuel wood supply.

The discount rate used in the calculations is 7% which reflect the assumed real rate of return that can be obtained on compensatory investment. The model for a one hectare government tree plantation from the SAR is used for the cost estimates. The present value of the cost of establishing one hectare of plantation is estimated at MK 894. In addition, the plantation has to bear the rental value of the land which is MK 10/year or a present value of MK 110 for twenty years. Hence, the present value costs of a plantation for twenty years are MK 1,004 per ha. The present value costs of establishing 80,200 ha of plantation in years 1, 2, 3, 4, 5, 21, 22, 23, 24, 25 and so on is about MK 461 million. Assuming that no expenditures need to be made for the maintenance of natural forests and the land of natural forests has no rental value, this present value cost is equated with the present value of the revenue stream obtained for 8.6 million m\(^3\) every year in perpetuity. The resulting sustainability premium is MK 3.62/m\(^3\). The required investment in fuel wood plantations is the sustainability premium times current fuel wood consumption.

The appropriate price for wood in this case would remain the marginal cost of sustainable fuel wood production (MK 15.3/m\(^3\)). If the price was set at the lower sustainability premium, an obvious inefficiency would arise since the marginal costs would significantly exceed the price and, thus, marginal benefits. This situation is different from the depletion of a non-renewable resource which, according to the sustainable supply rule, requires the early beneficiaries of abundant supply to subsidize the consumption of a substitute after depletion. There is no reason of inter-generational justice why the resource rent from sustainable yield of the natural forests should be used to subsidize contemporary production of fuel wood in plantations. Thus, prices should be set at the level of marginal costs.

Comments

The approach followed in this case study is a good example for the reversal in the default assumption about the value of natural capital. In a conventional analysis, the project is justified by enumerating the negative consequences of deforestation, assigning shadow values to these costs and comparing them to the project costs. In the original economic analysis this is done by calculating the increase in transportation costs, some assumed agricultural losses and increase in labour spent on fuel wood collection. As it is admitted in the original analysis, these benefits are representative rather than comprehensive. At least, sufficient direct benefits could be identified to arrive at a 10% ERR.
for the project. Under a sustainability constraint, the default assumption is that deforestation needs to be arrested. The project analysis has to settle the question whether this project is the least cost alternative for doing so. Hence, the project is compared to alternatives for achieving sustainability, and the burden of proof is reversed.

6.3 Yemen: Land and Water Conservation Project  
(May 7, 1992, SAR No. 9842-YEM)

The Project

The Land and Water Conservation Project contains support for various technical and institutional measures to increase the efficiency of water use in Yemen’s agriculture and improve management of forests. This case study focuses on the main project component which provides financing for improved ground-water irrigation conveyance systems. PVC and galvanized iron pipes are provided for 14,350 ha and will lead to net ground water irrigation savings of 15% in those areas. Pilot activities to increase water use efficiency through drip and sprinkler instead of flood irrigation systems are also included. According to the project documents, there is no systematic data available on the size of aquifers in the project area and on their recharge rates. However, evidence of water tables declining between one and seven meters per year indicates that ground water is being depleted rapidly. The project also includes institutional support for implementing first steps toward regulation of ground water use.

In the economic analysis of the project, it is stated that net water savings can be used to either increase the irrigated and cultivated area by 15% or reduce net depletion of aquifers by 15%. From previous experience, it is indicated that expansion of the irrigated area is likely to occur. While an increase in irrigated area is not explicitly supported by the project, no provisions are made against it either. For difficulties in evaluating reduced ground water extraction, the benefits from the increase in ground water use efficiency are evaluated in terms of an increase in irrigated areas of 15%. The resulting ERR of the project is 19%.

The Issues

Even though precise data is not available, there is no question that ground-water is being used unsustainably in the project areas. The project has the potential to alleviate the unsustainable situation but it will not necessarily do so. If the project leads to an increase in irrigated area, it will increase the investment sunk in an unsustainable irrigation system without contributing to a transition toward sustainability. On the other hand, with some additional conditions limiting area expansion, the project could reduce the unsustainable ground water extraction. If the water use efficiency increases achieved by the project were used to reduce net water extraction, this project would help alleviate an unsustainable situation.

The absence of data on aquifer size and recharge highlights the need to obtain such information before undertaking unsustainable depletion. Once the data is available, a sustainable price for water can be calculated based on desalinized seawater as a sustainable substitute. However, how should the project be evaluated without the required data? Under a sustainability constraint, ground water depletion would only be acceptable if a sustainable substitute such as desalinized seawater was provided after depletion. In the absence of any data but clear indication of rapid depletion, sustainability would require immediate conversion to sustainable depletion through
curtailment of consumption or provision of a sustainable substitute. The threat of seawater intrusion resulting from depletion of aquifers near the coast would cause irreversible damage that would give additional support for a strong sustainability constraint. A project that reduces ground water extraction would, therefore, be evaluated by comparing it with the best alternative for achieving sustainability. Two alternatives for achieving sustainability are the provision of desalinized seawater and the reduction of ground water extraction through reduction in irrigated areas. Both alternatives are considered in the following section.

Project Evaluation

<table>
<thead>
<tr>
<th>Year</th>
<th>Project Costs</th>
<th>Project Benefits</th>
<th>Net Benefits</th>
<th>Adjust Net Benefits</th>
<th>Net Adj Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26392</td>
<td>0</td>
<td>-26392</td>
<td>0</td>
<td>-26392</td>
</tr>
<tr>
<td>2</td>
<td>100944</td>
<td>4931</td>
<td>-96013</td>
<td>11113</td>
<td>-89831</td>
</tr>
<tr>
<td>3</td>
<td>107221</td>
<td>17439</td>
<td>-89782</td>
<td>22775</td>
<td>-64446</td>
</tr>
<tr>
<td>4</td>
<td>97105</td>
<td>35848</td>
<td>-61257</td>
<td>41799</td>
<td>-55306</td>
</tr>
<tr>
<td>5</td>
<td>83710</td>
<td>87359</td>
<td>3649</td>
<td>88669</td>
<td>4995</td>
</tr>
<tr>
<td>6</td>
<td>14610</td>
<td>68206</td>
<td>53596</td>
<td>69366</td>
<td>54756</td>
</tr>
<tr>
<td>7</td>
<td>5252</td>
<td>77100</td>
<td>71848</td>
<td>77775</td>
<td>72523</td>
</tr>
<tr>
<td>8</td>
<td>5252</td>
<td>82270</td>
<td>77018</td>
<td>82736</td>
<td>77484</td>
</tr>
<tr>
<td>9</td>
<td>5252</td>
<td>85833</td>
<td>80586</td>
<td>87377</td>
<td>82125</td>
</tr>
<tr>
<td>10</td>
<td>5252</td>
<td>126830</td>
<td>121578</td>
<td>126101</td>
<td>120869</td>
</tr>
<tr>
<td>11</td>
<td>5252</td>
<td>92049</td>
<td>86797</td>
<td>91516</td>
<td>86264</td>
</tr>
<tr>
<td>12</td>
<td>5252</td>
<td>87963</td>
<td>82711</td>
<td>87693</td>
<td>82441</td>
</tr>
<tr>
<td>13</td>
<td>5252</td>
<td>87246</td>
<td>81994</td>
<td>87239</td>
<td>81987</td>
</tr>
<tr>
<td>14</td>
<td>5252</td>
<td>91646</td>
<td>86394</td>
<td>93185</td>
<td>87933</td>
</tr>
<tr>
<td>15</td>
<td>5252</td>
<td>135866</td>
<td>130614</td>
<td>135138</td>
<td>129886</td>
</tr>
<tr>
<td>16</td>
<td>5252</td>
<td>104498</td>
<td>99246</td>
<td>103962</td>
<td>98710</td>
</tr>
<tr>
<td>17</td>
<td>5252</td>
<td>103088</td>
<td>97836</td>
<td>102817</td>
<td>97565</td>
</tr>
<tr>
<td>18</td>
<td>5252</td>
<td>103159</td>
<td>97907</td>
<td>103151</td>
<td>97899</td>
</tr>
<tr>
<td>19</td>
<td>5252</td>
<td>103101</td>
<td>97869</td>
<td>104639</td>
<td>99387</td>
</tr>
<tr>
<td>20</td>
<td>5252</td>
<td>144092</td>
<td>138840</td>
<td>121478</td>
<td>116226</td>
</tr>
</tbody>
</table>

Table 5 Adjusted Net Benefit Calculations

An alternative approach for achieving sustainability would be the reduction of the irrigated area. The irrigated areas are too dry for rain-fed agriculture. Therefore, the full economic benefit of production in these areas would be the cost of this approach and the net benefit from implementing the project since these costs would be saved. Hence, under a sustainability constraint, the project benefits would be evaluated as the benefits of not reducing the irrigated area by 15%. In the original analysis, project benefits were evaluated as the benefits of increasing the irrigated area by 15%. The only difference between both approaches is the time lag that occurs when new lands are developed. For the initial analysis, this time lag was assumed to be about one year. Now, the project benefits can be recalculated by counting the returns on 15% of the irrigated land one year earlier than in the original project analysis. This results in an increase of the projects ERR from 19% to approximately 20%. The adjusted net benefit calculations are shown in Table 5.

An alternative approach for achieving sustainability would be the provision of water from a sustainable source such as seawater desalination. A simple calculation shows that this is not a feasible
alternative. The cost of producing 1 m\(^3\) of freshwater from seawater is estimated at $1.05 to $1.6 [see World Resources Institute (1992), p.164]. Ignoring transportation costs and a sustainability premium for the use of unsustainable energy sources, this cost would be equivalent to YRI 19/m\(^3\). The net economic benefits from irrigation water differ widely between crops and regions from negative values to Yrl 7.2/m\(^3\). Hence, use of desalinized seawater is far more costly than reducing production of even the highest value crop.

Comments

This project demonstrates well the implications of a reversal in the burden of proof. The project should be compared to other approaches for achieving sustainability rather than to the without-project scenario. In this case, the numerical analysis is very similar with or without the sustainability constraint. The project increases the efficiency of water use; however, this will lead to water conservation only if water savings are used to reduce total water usage rather than increase the irrigated area. The main change to the project under a sustainability constraint would be the implementation of measures to ensure that water use efficiency gains would be used for a reduction in ground water extraction. The project also shows how to deal with a situation with very limited data availability. It highlights the need to gather data on the sustainability of current resource use before implementing a project that has ambiguous impacts on resource use.

6.4 Jamaica: Clarendon Alumina Production Project
(April 27, 1989, SAR No. 7195-JM, Loan No. 3062-JM)

The Project

The project consists of the investment plan of a joint venture between a government-owned company and a US aluminum producer (Alcoa) for sustaining the production of alumina from the Clarendon bauxite reserve. The project comprises bauxite mining in an open-pit mine and subsequent refining of bauxite and production of alumina. Alumina is exported and processed to aluminum ingot in the importing countries. Investments include completion of a red-mud lake for waste disposal and plant replacement and upgrading. The project contains a component for environmental protection, relocation costs for an adjacent community, and costs for the replacement of galvanized iron roofs in neighboring communities which are corroding due to emissions from the project. The project costs are $90 million of which $15 million is covered by the Bank loan. The project's estimated ERR is 54%. The project involves at least three different sustainability issues. Bauxite mining itself is unsustainable, however, a depletion premium is not included in the original project evaluation. Energy is used as an input to the project as well as in the smelting process in the countries importing alumina produced by the project. The energy needs to be evaluated at its sustainable price. Finally, emissions from the project need to be considered. In the original analysis, only corrosion damage to roofs in nearby settlements is included.

Evaluation of the Project under a Sustainability Constraint

a) Bauxite Depletion Premium

Jamaica's proven bauxite reserves are estimated at about 2 billion tons (about one tenth of world reserves), equivalent to a lifetime of about 100 years at the current rate of extraction. The projected price of alumina from the project is estimated at around $180/t. Two sustainable substitutes
for alumina can be envisaged. First, other materials, in particular recyclable synthetic fibers, can substitute for aluminum as light-weight construction material. Second, recycling of scrap aluminum can substitute for new alumina. Aluminum recycling is particularly attractive since smelting secondary aluminum requires only about 7% of the energy required for the entire process of producing a ton of aluminum from virgin materials [see Westenbarger et al. (1991) p.333]. The analysis by Westenbarger et al. (1991) shows that further significant increases in aluminum recycling can be expected as the infrastructure for recycling improves. Their calculations show a net welfare gain from increased aluminum recycling at current alumina prices. Based on this analysis and the expectation that progress in material technology over the next hundred years would be able to provide alternative sustainable materials, it is concluded that the cost of a sustainable substitute for alumina after bauxite depletion is not expected to exceed the current market price of alumina. As it turns out, a higher cost for producing a sustainable substitute would not materially affect the result of the following analysis anyway.

Even with the assumption that the cost of providing a sustainable substitute equals the current market price of the resource, a depletion premium should be considered if there are positive resource rents captured during depletion that would not accrue after depletion. For the Clarendon project, the bauxite extraction and alumina production costs are estimated at $130 per ton of alumina. With a market price of $180, there is a resource rent for bauxite equivalent to $50 per ton of alumina. A sustainability premium for depletion, \( P_s \), can be calculated by determining the share of the resource rent that needs to be invested in order to generate an equal net benefit stream after depletion. Hence, the present value of the stream of the depletion premium is equated with the present value of a compensation stream of resource rent minus depletion premium after the time of depletion. If this depletion premium was invested during depletion, a constant benefit stream of \( 50 - P \) times the amount of bauxite extracted per period would accrue in perpetuity.

\[
\int_0^{100} e^{-rt}P_s \, dt = \int_0^{100} e^{-rt}(50-P_s) \, dt
\]

\[
- P_s = e^{-r100} 50
\]

The depletion premium would be $0.38/t or $0.058/t at a 5% and 7% rate of return on compensating investment, respectively. With a depletion premium of less than 1% of the resource rent, it can be considered negligible and would not need to be considered further in evaluation of the project. However, actual compensating investment should still be made since the effect of interest compounding would result in a non-negligible compensation stream for future generations.

b) Energy Use

Aluminum production is a highly energy intensive process. Production of one ton of aluminum requires approximately 114 GJ of energy of which about 63 GJ are electricity used mainly

---

7 In this special case of an assumed constant resource price and an assumed cost of a sustainable substitute equal to the resource market price, the sustainable supply rule would be equivalent to El Serafy's approach for calculating the user cost for resource depletion for adjusting national income accounts [see El Serafy (1989)].
for electrolytic smelting of alumina [see OECD (1983)]. Theoretically, it would be required to assess unsustainable use of alumina produced under the project. Electricity for smelting is "often purchased at unusually low rates" [see Worldwatch Institute (1992), p.110]. However, most electricity used for aluminum smelters is from hydro energy and no explicit adjustment has been made to output prices for unsustainable use of alumina. However, the project itself has significant energy consumption as well. Since the Clarendon mine and plant are particularly energy efficient, an energy use of 24 GJ per ton of aluminum or 12 GJ per ton of alumina has been assumed for energy use within the project (only mining and refining of bauxite). This is equivalent to the use of two barrels of oil per ton of alumina produced. Project benefits can now be adjusted for a sustainability premium of $3.5 per barrel of oil. The derivation of this sustainability premium is explained in the case study: Malawi: Second Wood Energy Project. The calculation of project benefits only reflects the 50% government share of the joint venture that formed the basis for the economic analysis. However, project benefits include 33.3% income tax on the profits of Alcoa's share of the joint venture. Therefore, project benefits were also adjusted by one third of the sustainability premium of Alcoa's output share. The project's ERR would be reduced from 54% to 34% through the sustainability premium on use of fossil fuels.

c) Other Issues

Sulphur dioxide emission from the combustion of fossil fuels, possibly in combination with bauxite dust, has led to the premature corrosion of roofs in neighboring settlements. For example, roofs within 1/2 km of the plant need to be replaced every 3-5 instead of every 8-40 years. The project includes roof replacement costs and costs of equipment for emission reduction. However, a more systematic assessment of emissions would be necessary. It seems unlikely that emissions are severe enough to lead to rapid roof corrosion without i.e. impacting on agricultural productivity. In a more systematic assessment of emissions it should be attempted to account for the ultimate remaining of all emitted substances. For the emissions remaining after installation of abatement equipment, a cost for expected damage, which would most likely be higher than zero, should be imposed on the project. Alternatively, remaining emissions could be evaluated at the cost of emission reduction at other plants in Jamaica if abatement costs are lower at other locations. A quantitative analysis of emission costs is not yet included with this case study.

The project analysis includes a cost for land purchase. However, it is not clear whether the assumed value represents the full opportunity cost of land given that land scarcity is acknowledged elsewhere in the SAR: "An example of the dilemma posed by competing [land] needs was a recent interest by a Canadian outfit for bauxite land to grow the famous Jamaican citrus fruit "ortanique" for export to Canada. For viability, a minimum tenure on the lands of 20 years was required but this was not possible because the lands sought after were reserved for the [mining] companies' use in less than 20 years." (SAR, Annex 3, page 36). A market price for land would not cover the external benefits provided by the land in its previous use that would be foregone if the land is converted to mining and mud disposal sites. In particular, red-mud lakes (that are not very large) are considered to be almost impossible to reclaim. Therefore, a rehabilitation costs should be included in the evaluation of the project at the time of land use not at project completion (in order to allow other lands to fulfill the functions of the land used in mining). In the SAR, restoration or rehabilitation costs are not mentioned.
6.5 Ivory Coast: Fifth Oil Palm Development Project  
(September 18, 1985, SAR No. 5521-IVC, Loan No. 2627-IVC)

The Project

The project consists of the establishment (11,600 ha.) and replanting (15,000 ha.) of industrial oil palm plantations, replanting (29,100 ha.) and expansion (6,900 ha.) of small-holder oil palm plantings as well as establishment of medium sized private oil palm plantations (2,100 ha.). The total project area is 64,700 ha. The Bank loan constitutes US$ 13.4 million out of a total project cost of US$184.9 million. The economic rate of return to the project is estimated at 18.5%.

Issues

The principal sustainability issue in this project is land use. "An opportunity cost of land has not been included as the areas to be planted with oil palm are generally covered with degraded lush with limited commercial value." (SAR, para 6.02) Only foregone benefits from felling ageing trees are included in the analysis as opportunity costs. More specifically, "in about 33% of the project area, old palms will be replanted. In a further 33%, where densification of smallholder plantings will be carried out, the vegetation is a mixture of light forest, forest regrowth, perennial crops and annual crops. In the remaining area, forest which has been logged would be converted to oil palms." (SAR, Annex 3-1, para. 5.1) Soil protection is satisfactory (SAR, para. 6.07).

Under the given situation, two issues arise with respect to the treatment of opportunity cost of land. First, the project uses land that should be assigned an opportunity cost since, in the absence of the project, it could be used for other commercial uses (perennial and annual crops). While this opportunity cost may be small, it should be included as a matter of complete economic analysis. Otherwise, the economic analysis measures the return to land and capital and not the return to capital alone which would be needed for a sensible comparison with the social opportunity cost of capital. The second issue is shadow pricing of land that has no current commercial use. Under a sustainability constraint, no current commercial use would not be sufficient to assign an opportunity cost of zero to this land. It is unlikely that land in a densely populated country is not used at all, for example for fuel wood gathering. Even if there is no current human use, the wildland may contribute to the protection of biodiversity. The classification of land as "degraded bush" leaves open many questions that should have been reported in detail. It is not quite clear under which circumstances logging of the project area for establishment of new plantations occurred. Even though logging seems to have taken place before project appraisal, some deforestation equipment is actually part of the project itself.

Project Reassessment

To value land that apparently has little current commercial use, it is important to consider the pervasive and often intangible benefits provided by wildlands as habitats for preserving biodiversity and for soil and climate stabilization. Under a sustainability constraint, valuation of these benefits would not be based on the enumeration of individual benefits which is inherently incomplete due to the pervasiveness of these benefits. Rather, it would be assumed that the total remaining area of wildlands needs to be preserved. Then valuation of wildland would be based on the cost of restoring wildland elsewhere or on the cost of rehabilitating degraded cultivated land elsewhere which would reduce pressure to expand cultivation into previous wildlands.
A variety of cost estimates for land rehabilitation and restoration are provided by Doolette and Magrath (1990). Accordingly, the costs for different land protection measures range from $50 to $300 per hectare. The costs of land rehabilitation is estimated at $500 to several thousand dollars per hectare [see World Bank (1992), p.172]. Since the particular biological importance of wildlands used in this project is difficult to assess from the information given in the SAR, the ERR of the project has been recalculated for a range of land values between 0 and $3000/ha (shown in Figure 8). Table 6 shows the adjusted net benefit calculations for an assumed land value of $1000/ha (converted at the shadow exchange rate of CFAF 588) at which the project's ERR would be reduced from 18.5% to 13.8%. Under a sustainability constraint, it would be required to actually undertake activities that would restore an equivalent wildland area elsewhere or rehabilitate an equivalent area of degraded cultivated land.

7 Summary of the Treatment of Natural Capital Depletion in Other Bank Reports

Energy Projects

Reports on energy projects, in general, contain a detailed discussion of the energy reserves of the country. However, most reports do not consider a depletion premium or do not discuss the
approach used for arriving at such a depletion premium. Most of the analyzed reports do not discuss the potential of renewable energy resources in the respective country. This, however, should be part of an analysis of the energy sector and could serve as the basis for the calculation of sustainability premia for energy resource depletion projects. Sulphur dioxide and other emissions as well as measures taken for pollution abatement are often discussed. However, no report was found that explicitly evaluates expected damage from remaining emissions. Carbon dioxide emissions are ignored in almost all analyzed reports.

Bolivia: Vuelta Grande Gas Recycling Project (June 4, 1986, SAR No. 6181-BO)

The project consists of gas processing and injection plants that would increase the amount of hydrocarbons that can be recovered from the Vuelta Grande oilfield. The economic rate of return on the project is 21% on a full cost basis and 60% if sunk costs are excluded. The calculation of the economic rate of return includes an unspecified depletion allowance that was determined by "estimating of exploration wells needed to discover the energy depleted based on historical ratios of gas and oil found per average exploration well in Bolivia". (SAR para. 5.3)
India: Western Gas Development Project (January 11, 1987, SAR No. 6503-IN, Loan 2904-IN)

Under the Project, gas production will be increased through expansion and development of several gas fields. India's gas reserves are currently estimated at 550 billion cubic meter (BCM). The project will significantly contribute to increasing annual production from currently 8 BCM to 20 BCM per year. This would imply a static lifetime of reserves of 34 years. The economic analysis does neither mention nor include a depletion premium for gas extraction. The economic rate of return varies by project component, between 36% and 82%.

India: Coal Mining and Coal Quality Improvement Project (March 25, 1987, SAR No. 5843-IN, Loan No. 2796-IN)

The project consists of the expansion of the Gevra open-pit coal mine to feed a power plant and the development of the Sonepur-Bazari open-pit coal mine. India's coal resources are estimated at 127 billion tons (excluding lignites) of which 60 billion tons are classified as reserves. At the current production of 153 million tons per year, the static lifetime of the reserves are 392 years. In face of increasing demand (currently rising at 9% per annum), the SAR estimates the lifetime of reserves at 100 to 150 years at least. New coal fields tend to be of lower grade coal. Despite an increasing stripping ratio, operation costs (per ton of coal) are expected to decline with increasing operation efficiency. Both mines include some equipment for land reclamation. The two project sites cover 10.8 and 19 km², respectively. Together, both mines require resettlement and compensation of 2,000 families. The costs of acquiring land and compensating families to be resettled are apparently included in the analysis. A depletion premium for coal extraction is neither discussed nor included. Environmental concerns about air pollution resulting from coal combustion or carbon dioxide emissions are not discussed. (Already in 1985 there was far-reaching consensus on the greenhouse effect even though the problem was not yet as widely known as today.) The economic rates of return are 19% for the Sonepur-Bazari and 32% for the Gevra mine.

Burma: Gas Development and Utilization Project (May 21, 1987, SAR 6672-BA, Credit No. 1840-BA)

The project involves the further development of the Payagon gas field to increase gas production by 12.8 BCM per year. Burma's natural gas reserves are 280 BCM. Gas development is at an early stage with production of 1.2 BCM per year. A depletion premium is not included in the calculation of economic rates of return. However, the SAR contains a discussion of the depletion premium in the context of long-run marginal costs of gas in Burma (para. 5.11). There it is stated that a depletion premium would be "insignificant or inappropriate" in face of current reserves of 150 years. The project has two components with rates of return of 55% and 72% respectively.

Poland: Energy Resource Development (May 7, 1990, Project SAR No.8343-POL)

The project covers development and rehabilitation of gas fields, improvements in gas transmission and processing as well as technical assistance. The project would result in significant increases in gas and condensate extraction. Gas produced under the project will mostly substitute for domestic coal consumption, resulting in a corresponding increase of coal exports. Reserve characteristics of various energy resources are discussed in detail. However, a depletion premium for gas to be produced under the project is neither discussed nor included in the economic analysis. At current extraction of approximately 5 BCM per year, Poland's gas reserves of about 250 BCM would
last for 50 years. The estimated ERR is 37%. Reductions in emissions resulting from substitution of coal are considered a non-monetary benefit of the project. However, coal that was previously consumed domestically, will be exported under the project. Therefore, emissions are not avoided but moved to another location. In particular, the mentioned reduction in carbon dioxide emission is spurious since only global net emission reductions would constitute a true project benefit.

**Indonesia: Gas Utilization Project** (May 8, 1990, SAR No. 8112-IND)

The project supports the development of gas distribution systems. It does not directly include gas field development. However, gas production is expected to increase as a result of the project. Gas supply to the project is considered surplus to Indonesia's export requirements and thus non-tradable. Gas supply is priced at its long-run marginal cost estimated at $1.50 per thousand cubic feet (energy content of 1.1 GJ, equivalent to 0.18 bbl oil), or $9/BOE. This cost is supposed to include a depletion premium. The assumed depletion premium or the approach used for arriving at it, however, is not provided. The resulting ERR of the project is 59%.

**Yugoslavia: Kolubara B Thermal Power and Lignite Mining Project,** (May 20, 1991, SAR No. 9420-YU)

This project consists of the construction of a 7 million ton per year lignite mine and a mine head thermal power plant in Serbia. The base case ERR is 14.5%. The reserves of the lignite mine would last approximately 50 years. Lignite is treated as a free input to the project with the justification that a mine head power plant is the only economic use for lignite since transport costs for lignite are prohibitive above 50 km. Land use is not explicitly included as a cost in the analysis. However, some resettlement costs are included. Also, reference is made to satisfactory land reclamation practices by the mine operator. The mine supplies lignite with a relatively low sulphur content (0.5%). SO$_2$, NO, and dust emissions are discussed extensively. The power plant is expected to meet international emission standards. However, implementation of EC emission standards may require later installation of flue gas desulphurization which would increase project costs by about 13% and reduce the ERR to 11.6%. The external damage costs arising from remaining emission are not considered. Carbon dioxide emissions are not discussed. The mine would reduce water quality in surface aquifers. As an alternative water supply, the borrower has drilled wells to deeper aquifers. The power plant has been identified as part of a least-cost power expansion strategy. However, electricity demand is considered exogenous and no reference is made to demand side management strategies.

**Malaysia: Gas Utilization Study** (September 16, 1991, Report No. 9645-MA)

This study analyzes the gas sector in Malaysia and proposes a gas utilization strategy. The report is the only one of those listed in this paper that explicitly refers to the economic theory of natural resource depletion and the costs imposed on future generations through resource depletion. The report rightly describes the economic cost of gas as consisting of two components: the cost of production and transmission and a depletion premium. The depletion premium is calculated by discounting the cost of a substitute fuel at the time of depletion (assumed to occur in the year 2018). Imported coal is assumed to be the least-cost substitute. The additional capital costs for achieving emission standards with coal fired power plants are considered. The coal price forecasts that were used imply an increase of 1% per annum. The opportunity costs of depletion are discounted at 5% (not at Malaysia's assumed opportunity cost of capital of 10%). The calculated depletion premium
ranges from M$2.05 to M$2.99 per million BTU. This is 30-50% of current gas prices and equivalent to US$4.5-6 per BOE.

Mining Projects

The reports on extraction projects for non-energy resources, in general, provide far less information on the extent of reserves in the respective country than reports on energy projects. No report could be found that contained discussion of a depletion premium. Also opportunity costs of land and the costs of land rehabilitation are often ignored. To allow an assessment of possible violations of a sustainability constraint, project reports should clearly spell out reserve size, land use, rehabilitation costs or mention explicitly which data is not available and needs to be obtained. Under a sustainability constraint, land restoration costs would have to be accounted for at the beginning of the mining project, not at the time of completion when it is often economically insignificant due to the effect of discounting.

Brazil: Carajas Iron Ore Project (July 6, 1982, SAR No. 3921-BR)

As part of the gigantic Grande Carajas Program, the project consists of the integrated development of the Carajas iron ore project within the Eastern Amazon including mining, rail road and port equipment. The project provides infrastructure for the further development of the region. The project’s ERR is calculated as 13% for the base case. Minerals are treated as free input to the project. Total iron ore reserves in Carajas are estimated at 18 billion tons. In the long term, the project would extract 50 million tons of ore per year. Ultimate disposal of tailings is not discussed in detail. Power is supplied to the project at an unspecified price from the Tucurui hydro-electric dam. The project contains a component on environmental management for the immediate environmental impacts of the project as well as a "Carajas Amerindian Sub-Project". The environmental activities under the project are described, however, the SAR does not contain a discussion of the environmental impacts of the project. There is neither a qualitative nor a quantitative discussion of the ecological costs of the Amazon development program. Costs for land or land restoration are not explicitly included in the analysis. The total area of land withdrawn from the natural systems for the purpose of the project is not apparent from the SAR nor is current land use discussed (presumably forests).

China: Hubei Phosphate Project (April 25, 1989, SAR No. 7417-CHA)

The project supports development of two major phosphate mines and downstream fertilizer production for domestic consumption. Phosphate reserves in China are estimated at 200 times current annual extraction. The project will increase extraction by approximately 15%. The project’s ERR of 16.7% is calculated without consideration of a user cost. The current or possible alternative land use of the area on which the open pit mine is to be opened is not mentioned. Subsequently, an opportunity cost of land is not included in either FRR or ERR calculations. Restoration or rehabilitation of land is not mentioned.

Jordan: Integrated Phosphate Project (January 8, 1990, SAR No. 8190-JO)

The project consists of the rehabilitation of a fertilizer plant and the development of a phosphate deposit, enabling Jordan to increase exports of phosphate rock. The phosphate reserves are described as vast but no quantification of the reserves is given. The report indicates that the
declining grade of Jordan's phosphate rock requires more costly beneficitation. The financial rate of return considers the production tax levied by the government on phosphate production. There is no consideration of a user cost in the economic analysis, even though the increasing cost of beneficitation would imply the existence of an opportunity cost. The ERR for the project component covering mining and beneficitation is 26.1%, reflecting a considerable amount of sunk cost in mine development under a previous Bank loan. The phosphate mine is located in a barren desert area, devoid of sedentary population, vegetation and water courses. Under these extraordinary conditions, the assumption of zero opportunity cost of land appears justified. Slimes from the beneficitation plant will be discharged into a depression close to the project area.

Jordan: Dead Sea Industrial Exports Project (June 5, 1991, SAR No.9451-JO)

The project supports expansion of the production facilities for potash and the development of chemical industries based on Dead Sea brines. The raw material for production under the project is Dead Sea brine. "Its security of supply, at no cost, for the mother brine is guaranteed for a great many years while the Dead Sea exists." (SAR para 4.05) The executing company holds the sole Jordanian concession to process the brines for 100 years. Neither this concession, nor the brine is included as a cost in the economic analysis. However, the true scarcity of the raw material and the opportunity cost of the concession are difficult to assess based on the information provided. Water supply for the plant is critical since fresh water resources are scarce. While the projects provides facilities for drilling, transport and storage for fresh water, an explicit cost for depleting ground water is not included in the analysis. The evaporation ponds for the project occupy a significant part of the Dead Sea's surface area. This land use is not evaluated; however, it is not clear, whether the occupied area will be expanded as a result of the project. The project's ERR is estimated at 17%.

8 Conclusion and Extensions

In summary, the analyzed World Bank reports show a surprising lack of completeness and sophistication of environmental valuation in the economic analysis of Bank projects. 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 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 practical context of project evaluation in developing countries. On the other hand, neglect of environmental evaluation leads to a systematic and, as some of the case studies show, a 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 discussed in this paper.

The case studies in this paper show that sensible estimates of shadow prices for natural capital can be derived from a sustainability constraint as a rule for evaluation under considerable uncertainty. However, in order to improve the quality of environmental evaluation in project analysis, a more systematic approach is needed for those cases where more conventional approaches for environmental valuation fail because of the involved uncertainty or implications for inter-generational 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 shadow prices for
natural capital from scratch. 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 an "Sustainability Pricing Manual" for World Bank 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.

For truly global forms of natural capital, uniform shadow prices should be used throughout the Bank. For example, carbon dioxide emissions should be treated uniformly and would be evaluated following the methodologies outlined in this paper. For more regional forms of natural capital, such as emissions of sulphur dioxides, depletion of natural resources or use of local wildlands, generic calculations should be provided that can be easily adapted for a specific project. The Environment Department would be well positioned to compile the proposed "Sustainability Pricing Manual". The concern about the significant uncertainties involving these calculations is valid but ultimately unjustified since any new methodology should be compared to the current approach of almost complete ignorance.

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 a 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 inter-generational 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 practice 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 conversion to a substituting sustainable activity. The rule is suitable as a preemptive measure against the biases in evaluating natural capital that were discussed in Section 2. Using the sustainable supply rule, differences in relative scarcity of different resources would be appropriately reflected in the sustainable price. The sustainable supply rule alleviates the inter-generational 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 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 future functional substitution 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 substitutability, 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, a concept that is intuitively appealing in face 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 equal allocation of resources to all generations.

More practical issues to be addressed include the institutional arrangements for implementation of the inter-generational 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 (1992b)], I try to answer the question whether the allocation of inter-generational property rights and creation of inter-generational 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.

Hopefully, the paper 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 impoverishing this planet for generations to come. The paper does not directly address the issues of intra-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. More explicitly, the sustainable supply rule could be modified such that a 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 nations.
Appendix A  Derivation of the Sustainable Supply Curve

This appendix provides the formal derivation of the sustainable supply rule. In the simplest case, the non-renewable resource is homogeneous with zero extraction costs and supply of the sustainable substitute is infinitely elastic at $C_s$. 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 $R/M$ periods. The present value of the compensation component, $K$, from time 0 to $R/M$ is

$$K = \int_0^{\frac{R}{M}} e^{-rt} MP_s \, dt = \frac{MP_s}{r} \left(1 - e^{-r\frac{R}{M}}\right) \tag{12}$$

where $P_s$ is the sustainable price, $r$ is the (continuous time) rate of return on investment in sustainable substitutes, $R$ is the total stock of the non-renewable resource, $M$ is the rate of extraction, and $R/M$ is, therefore, the lifetime of the resource. The present value of the subsidy stream, $S$, from time $R/M$ until infinity is

$$S = \int_{\frac{R}{M}}^{\infty} e^{-rt} M(C_s-P_s) = e^{-r\frac{R}{M}} \frac{M(C_s-P_s)}{r} \tag{13}$$

Equating $S$ and $K$ and dividing both sides by $M/r$

$$P_s \left(1 - e^{-r\frac{R}{M}}\right) = e^{-r\frac{R}{M}} C_s - P_s \tag{14}$$

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

$$P_s = e^{-r\frac{R}{M}} C_s \tag{15}$$

If there is a constant extraction cost, $E$, per one unit of the non-renewable resource, the compensation component is:

$$K = \frac{M(P_s-E)}{r} \left(1 - e^{-r\frac{R}{M}}\right) \tag{16}$$
Similarly, $P_s$ is calculated,

$$P_s = E + e^{-x_s} (C_s - E)$$

(17)

where $P_s$ is total price including extraction cost. The appropriate user cost is $P_s - E$. 

64
Appendix B  Comparison with the El Serafy-Mikesell Approach

The sustainable supply rule for a non-renewable resource with zero extraction cost follows El Serafy's (1989) proposal for modification of national income accounting for depletion of non-renewable resources. The purpose of this Appendix is to clarify the differences between El Serafy's approach and the sustainable supply rule. I will present an argument against directly applying the El Serafy approach to project evaluation as suggested by Mikesell (1991). El Serafy defines income as that portion of revenues from a non-renewable resource that does not need to be invested for the generation of a perpetual income stream of returns of an amount equal to the income. Equating the present value of the finite stream of revenues, R, of the resource over n periods (lifetime of the resource until depletion) with the present value of a perpetuity, I, at the discount rate r allows calculation of the appropriate I that may be accounted for as income

\[
\frac{R}{r} \left(1 - \frac{1}{(1+r)^{n+1}}\right) = \frac{I}{r}
\]

(18)

hence, the share of revenues that can be counted as income is

\[
\frac{I}{R} = 1 - \frac{1}{(1+r)^{n+1}}
\]

(19)

Mikesell proposes use of these equations to adjust the net social benefits of a project for resource depletion. (In a pure extraction project, R would be the project's original NPV and I the adjusted NPV.) The right hand side of equation (19) is always positive. Therefore, it follows from the same equation that if R is positive, I is positive. Therefore, this adjustment of a project's NPV would never change the sign of the NPV and, hence, never reverse the desirability of a project.

Accounting measures, such as national income or GNP, are based on market prices and are supposed to provide ex-post information about sustainable consumption opportunities. El Serafy adjusts national income appropriately by calculating a share of revenues (exchange value: marginal cost or marginal benefits times quantity) attributable to depletion. Economic analysis, such as project evaluation, in contrast, is used for normative ex-ante maximization. This includes the decision as to how much of a non-renewable resource to use. As a normative concept, economic analysis is based on rent calculation (total benefits or use value). Adjustments to economic analysis, therefore, require corresponding adjustments to rents from natural capital. While efficient allocation is based on equalization of marginal values, the concept of equity is based on equalization of total benefits. Hence, a sustainability constraint for ensuring inter-generational justice has to be based on total benefits or rents and not on marginal benefits or revenues.

If adjustments based on exchange value are applied to normative project analysis, as in Mikesell (1991), non-intuitive results can follow. For example, with constant expected resource prices, maximizing NPV would require immediate depletion of all non-renewable resources and conversion into interest bearing investment. Such result of a sustainability rule is clearly unappealing. It, however, follows from considering only the exchange value for calculation of the maximum income component. On the other hand, if price increases are assumed (i.e. following the Hotelling rule), long-lived projects may not be burdened with any significant benefit reduction since high future

65
revenues (because of increasing prices) would provide the funds for the capital (compensation) component. This would defy the purpose of inter-generational justice since early generations would enjoy larger benefits while having to invest less as compensation than later generations. The difference between evaluation based on marginal benefits (revenues) versus total benefits (rents) is most obvious for supposedly free goods. If no price is charged for a resource, it would be used until marginal benefits from its consumption are zero. Compensation based on exchange value would not be required for such a resource since revenues are zero. Compensation based on total benefits would, however, be larger than if a market price existed and consumption was accordingly reduced. An exchange-value based rule is unsuitable for the evaluation of unsustainable activities for which no market price exists; the sustainable supply rule based on rent adjustments is preferable.
References


Daly, Herman E. and John B. Cobb, 1989, For the Common Good, Beacon Press.


Markandya, Anil and David Pearce, 1988, Environmental Considerations and the Choice of the Social
Discount Rate in Developing Countries, World Bank, Environment Department WP No.3.


Ogden, Joan M. and Robert H. Williams, 1989, Solar Hydrogen, Moving Beyond Fossil Fuels, World Resources Institute, Washington DC.


Worldwatch Institute, several years, State of the World 19xx, Washington DC.6