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Commentary

Defining the generational environmental debt ☆

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Abstract

Assume that we have borrowed the Earth from our children, and that we one day shall give it back to them and account for what we have done to it. Then we would have to try to restore the damage we have caused. Further, we would have to offer compensation for the damage we have done that we cannot repair at a lower cost. The generational environmental debt (GED) is a measure of these costs. In this paper we define and discuss the concept of GED and calculate GED for emissions of the greenhouse gas CO_2. The global GED for CO_2 emissions is estimated to 10000 billion US dollars and the Swedish GED for CO_2 emissions is estimated to 60 billion US dollars.

Keywords: Generation; Environment; Debt; Natural capital

1. Introduction

For some time now it has been understood that the present societal use of resources and manipulation of nature is not sustainable in the long run. The main mechanism behind this is that the costs associated with the unsustainable activities do not affect those that carry out the activities. Several researchers have responded to this deficiency by proposing methods for internalising costs that are not included in the market prices (e.g., Pigou, 1920). Methods have also been proposed for modifying the system of national accounts, in monetary terms (e.g., Hueting and Bosch, 1994) as well as in physical terms (e.g., Longva, 1981), so that it includes environmental degradation.

In earlier work (Holmberg and Karlsson, 1992; Holmberg et al., 1994), we have argued that there is a need for physical indicators of sustainability. In this paper we define a method for calculating the monetary cost associated with the changes in these indicator values. These costs will, to a large extent, affect future generations and people living in other countries. The environmental damage that will affect future generations will give rise to a *generational* environmental debt (GED). In this paper we present a method of calculating this debt. This method can also be used for calculating the *foreign* environmental debt (FED).

GED is conceptually different from the proposals to modify GDP into a green GDP or other alternative measures, such as that of a sustainable national income (Hueting and Bosch, 1994). Loosely speaking, GED is a measure of the total

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amount of environmental damage that past and present generations have caused, but that will affect future generations.

Jernelöv (1992) introduced the concept of GED and defined it as the cost required to restore the environmental damage that is economically and technically restorable, as well as the size of the capital required for recurring restoration measures. He estimated the Swedish GED to be approximately 32 billion US dollars in 1990. The most important items were: emissions of the greenhouse gas CO_2 (10 billion US dollars), acidification (6 billion US dollars), increase of cadmium and decrease of humus on agricultural land (1 + 3 billion US dollars) and handling of waste, including radioactive waste (10 billion US dollars). Furthermore, he estimated the annual increase, "if we do not act," at 1 billion US dollars. Jernelöv concluded that pollution and interference with the environment lead to reduced future possibilities for high production and material standard of living and that Swedes, in this respect, are still borrowing from future generations. Inspired by Jernelöv's work, we try to further develop the concept.

We define GED as the least cost of the sum of a combination of the cost of restoration and the cost of damage. In most cases this means that restoration should be made until the marginal cost and the marginal benefit of restoration are equal. In these cases GED equals the sum of the cost of restoration and the cost of the remaining damage.

In the following section we define GED and discuss how far restoration should be made. It also contains a discussion on the different types of damages that have to be included in the evaluation of GED, which reference system and time perspective should be used and the appropriate choice of discount rate. In the third section we discuss how GED can be calculated for individual countries. In Section 4, the possibility of aggregating GED with other generational transfers, such as human-made capital, in order to find the total generational transfer is discussed. In the Appendix we use this definition to calculate GED for emissions of the greenhouse gas CO_2. The global GED for CO_2 emissions is estimated to be 10 000 billion US dollars and the Swedish GED for CO_2 emissions is estimated at 60 billion US dollars.

2. Method of calculation

2.1. Defining the generational environmental debt (GED)

In this section we present a method for calculating GED. The present generation can either restore the damage or compensate future generations for the damage we have caused. When shall damage be restored and when shall it be compensated for? And if restoration is chosen, how far should it be taken?

Fig. 1 is an illustration of GED for specific damage. The benefit of restoration is given by the damage that is avoided. It is reasonable to assume that the marginal benefit of restoration decreases and that the marginal cost of restoration increases with the degree of restoration. The definition of GED implies that the present generation should restore a specific damage until the marginal benefit of restoration equals the marginal cost of restoration (restoration degree x in Fig. 1.) Thus, GED for each specific damage is equal to the sum of the cost of restoration (area

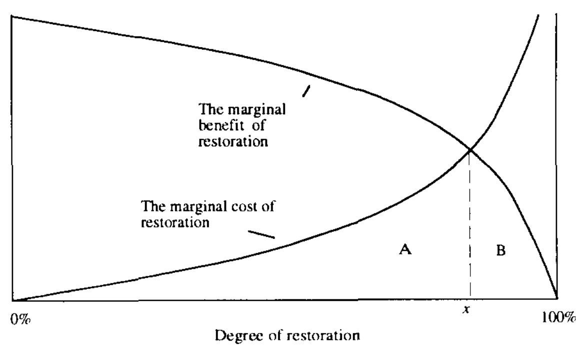

Fig. 1. GED for specific damage. GED for each case of specific damage is equal to the sum of the cost of x restoration (area A) and the cost of the remaining damage (area B). The total GED is then given by adding GED for all specific damage. If the marginal cost of restoration initially is higher than the marginal benefit of restoration then it is the strategy that minimizes the debt that should be used.

A) and the cost of the remaining damage (area B). If the marginal cost of restoration is higher than the marginal benefit of restoration for every degree of restoration, then GED is equal to the total damage caused. The total GED is given by adding GED for all specific damage.

Jernelöv (1992) used another method to calculate GED. He calculated the cost of restoring the damage that can technically and economically be restored. This means that Jernelöv excluded damage that is impossible to restore (e.g., extinction of species and the destruction of the ozone layer) from his calculation of GED. But for the damage that is included, his definition of GED approximates area A, with the sole difference that the degree of restoration, x, is not given by the intersection between the curves in Fig. 1, but again by what is technically and economically motivated. Depending on how far restoration is taken, Jernelöv's method can give a higher as well as a lower value for GED, but the cost of the remaining damage is never included.

For situations where there are no technical means of restoring specific damage, our definition of GED is more useful than the method used by Jernelöv. The depletion of the ozone layer is an illustrative example. It could cause hundreds of thousands cases of cancer (Kerr, 1991). With the method used by Jernelöv, the depletion of the ozone layer is not included in GED since it is not technically possible to restore. With our approach —i.e., to choose the cheapest alternative—the cost of damage becomes a more useful measure of GED.

2.2. Identified and potential damage

The societal relation to nature is characterised by *exchange* of substances and by *manipulation* (Holmberg and Karlsson, 1992) (see Fig. 2). The exchange takes place in the form of flows of energy and materials. Resources are *extracted* from deposits (minerals, ores, etc.), funds (forests, fish populations, etc.) and natural flows (sunlight, winds, etc.) for use in society. The natural flows are continuously flowing, the funds have a limited regrowing potential and the deposits are gradually depleted when extracted. Matter is conserved; this implies that extracted materials that are not stored in society are returned to nature. This *return flow* of matter to nature may, for example, consist of discharges of heavy metals.

The societal manipulation of nature includes: (a) *displacement* of nature (societal activities force away or disturb ecological systems or geophysical functions, e.g., by constructions of highways), (b) *reshaping* of the structures of nature (e.g., damming of rivers, ditching, ploughing) and (c) *guiding* of processes and flows (e.g., agricultural practices, manipulation of genes).

Nature has a limited resource-creating capacity for the substances that society extracts and a limited assimilation capacity for the substances that society returns to nature. Furthermore, the stabilising capacity of nature is often reduced when it is manipulated (e.g., through the loss of biodiversity). When the societal influence exceeds these capacities of nature, damage occurs.

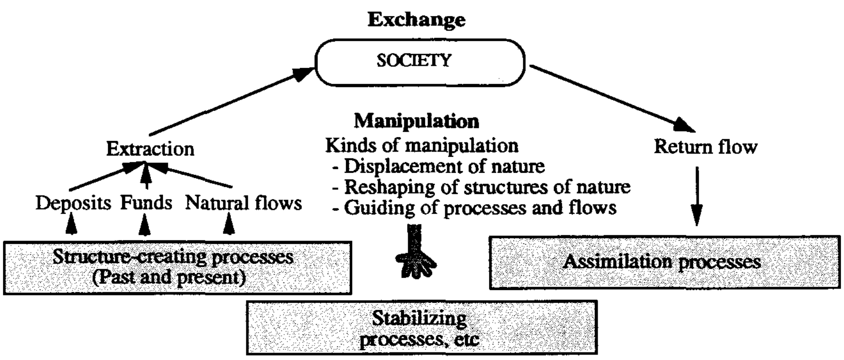

Fig. 2. General mechanisms for the physical influence of society on nature. Based on Holmberg and Karlsson (1992).

There are two types of damage that should be included in GED. Some instances of damage are discovered— we call them *identified damage*. But quite often impacts on nature have unknown effects. Trends such as increasing concentrations of a substance in nature will most likely cause damage, if they continue to increase. Trends that are known, and that have not yet caused any identified damage, are defined as *potential damage*. Because of the complexity and the delay mechanisms in nature, it is extremely hard to identify the level of concentration at which changes in the ecosystem will occur, and what kind of damage might arise. Thus, when estimating the contribution to GED of potential damage it is necessary to focus on the trend. Usually, we do not know the critical concentration, and therefore a trend of this kind implies a risk (Holmberg et al., 1994).

The discharges of CFC-molecules were a potential damage until we identified that CFC-molecules had a negative impact on the ozone layer; at that moment this potential damage turned into an identified damage.

We also note that for certain concentrations substances A and B might be non-hazardous in isolation, but together they might have negative impacts (synergism). If we emit substance A, and future generations emit substance B, damage will arise if substance A remains long enough. It could also be the case that for the present concentration of A in the ecosphere, no damage will occur, but that there is a threshold above which it is harmful. Then if future generations continue to emit that substance, damage will eventually arise. Similar examples could be given from other types of human influence on nature than emissions of a certain substance. This means that our influence on nature may aggravate the damage that future generations will cause. These trends could be seen as a reduction of the assimilating and stabilising capacity of the ecosphere.

Thus, there are two reasons for including potential damage in GED even if it has not yet caused any identified damage: (a) it might do so in the future due to long time delays and (b) the reduction of the assimilating and stabilising capacity of the ecosphere.

When calculating the cost of the identified damage and the potential damage we must distinguish between the cost of restoration and the cost of damage (see Fig. 3). For the identified damage and the potential damage that can be restored, it is possible to calculate a restoration cost. For the identified damage it is also possible to calculate a cost of damage, but this is not possible for the potential damage. It is a desirable task to find indirect ways of estimating the damage cost of the potential damage in relation to the cost of restoring it, since this has to be done when calculating GED (as well as when calculating changes in the stock of natural capital). One way would be to use the risk assessment of the potential damage as a measure of its damage cost.

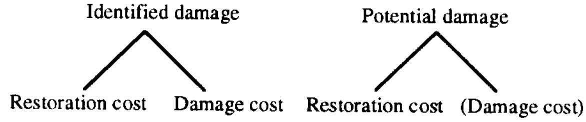

Fig. 3. The components of GED.

2.3. Reference system

When calculating GED, the choice of reference system is essential. We argue that GED should only include damage that is caused by human influence. Therefore damage due to, for example, volcanic activities, should not be included in GED. We can look at a specific problem: the greenhouse gas CO_2, to make the discussion more concrete. Should a country which presently has a high natural [1] net fixation of CO_2 in its forests have a smaller GED for CO_2 than a country with the same CO_2 emission from fossil fuels, but with a smaller natural net fixation of CO_2. That is, should people living in Sweden be allowed to emit more CO_2 from fossil fuels than people living in Syria because of the present greater net fixation of CO_2 in Swedish ecosystems? We argue that the answer to this question depends on whether the differences are caused by human manipulation or not.

[1] Natural fixation includes all processes that are not due to human manipulation.

However, if we only consider the emissions of CO_2 from fossil fuels when calculating GED, net emissions of CO_2 from manipulated ecosystems (e.g., deforestation) would not be included. Hence, we argue that emissions of CO_2 from fossil fuels and cement production, etc., as well as net emissions or net absorption of CO_2 resulting from anthropogenic changes in ecosystems (e.g., deforestation and decreased humus layer in agricultural areas or reforestation and increased humus layer) should be included in the calculation of GED for CO_2.

At present, there is a net fixation of carbon in Swedish forests. But if no forestry had occurred, the carbon content in Swedish forests would have been higher (Linder and Östlund, 1992; Lundström, 1993). This aspect must be considered when GED is calculated. At a first glance, this would imply that Sweden has a higher GED for CO_2 emissions. On the other hand, some of the carbon that has been taken from Swedish forests is stored in society. We assume that these two aspects cancel each other out. Therefore, we only consider emissions of lithospheric carbon in the calculation of the Swedish GED for CO_2 in the Appendix.

2.4. Time perspective

This paper discusses intergenerational issues. But, on a societal level, there are no distinct moments in time when one generation leaves and another takes over. What is the time span of one generation?

GED could be calculated as the accumulated debt. This means that GED is considered as the sum of the damage that the present *and* the past generations have caused. It might be considered as an injustice to the present generation that we should pay for the debts of past generations, but since almost all negative environmental effects with long-term impacts have been caused during the last 50 years, it may be reasonable to hold our generation responsible for the accumulated GED. It could also be said that if we do not take responsibility for the debt of past generations, who should?

The year from which one chooses to start the calculation of GED is, of course, crucial, but there are no obvious guidelines for making this choice. Therefore, it is of importance that the "starting year" is highlighted. This could be done by adding it to the title (e.g., "GED for Sweden since 1900"). It is also important that the calculations are consistent, i.e., all terms are calculated from the same starting year.

One way of getting around the problems associated with the choice of starting year could be to focus on the *change* in the accumulated GED. It is probably difficult to get meaningful estimates for the annual change in GED. We therefore suggest that it could be calculated every decade, say beginning with the year 2000 and then onwards. This way of dividing time gives us 10 years to plan how to reduce our GED: i.e., the possibility of reducing future expected emissions might be cheaper than compensating for the expected GED at the end of each time period. It is often the case that avoiding the damage, *the avoidance cost*, is cheaper than causing the damage and then restoring or compensating for it.

2.5. Method of discounting

Since we are dealing with intergenerational pollution and resource depletion, the choice of discount rate is crucial to the cost analysis. In most economic literature a constant discount rate is used despite the fact that the growth rate in the economy most often varies. On shorter time scales, this approximation is likely to be valid, but on longer time scales (50 years or more) it is not, since an exponential growth rate cannot go on endlessly. Here we choose a method of discounting that is general enough to take possible changes in the growth rate into account (Azar, 1994a; Sterner, 1994). According to the so-called Ramsey rule, the discount rate $r(t)$, is given by:

$$r(t) = \gamma g(t) + \rho(t) = \gamma \frac{\dot{c}}{c} + \rho(t), \tag{1}$$

where γ is the negative of the elasticity of marginal utility of consumption, $c(t)$ is global per capita consumption, $g(t)$ the per capita relative growth rate in consumption and $\rho(t)$ the pure time preference. The first term stems from the expectation that we will be richer in the future and that the marginal utility is positive but its derivative negative. The second term stems from impatience. All variables are generally time-dependent, but here we assume γ to be constant.

We have chosen $\rho = 0$. There are three main reasons for this choice. First of all, when intergenerational issues are discussed, the use of a pure time preference is unethical. Why should the happiness of future generations be less worth than the happiness of the present generation? Secondly, using a pure time preference would be inconsistent with our starting point since the entire approach is built on the assumption that we should pass on the Earth to the following generation in a condition that is not worse than it was when we borrowed it. Thirdly, future generations would not accept having "their own present" discounted by reasons related to our impatience. The only possible outcome of an imagined negotiation between the present and the future generations would be to make $\rho = 0$. The position that $\rho = 0$ has been taken by several authors, such as Ramsey (1928), Spash and d'Arge (1989), Broome (1992), Cline (1992), Eriksson (1994) and Azar (1994b).

This however does not mean that the discount rate generally is zero since one can expect the per capita income to change. The present value factor of a cost occurring at time t (for $\rho = 0$) is given by the following expression:

$$V(t) = \exp\left(-\int_0^t r(t')\,\mathrm{d}t'\right) = \left[\frac{c_0}{c(t)}\right]^{\gamma} = \left[\frac{C_0}{C(t)}\right]^{\gamma}\left[\frac{P(t)}{P_0}\right]^{\gamma} \tag{2}$$

where upper case C represents global consumption and $P(t)$ the world population. If we assume that $C_0/C(t) = y_0/y(t)$, where $y(t)$ is the gross world product (GWP), Equation (2) can be rewritten as:

$$V(t) = \exp\left(-\int_0^t r(t')\,\mathrm{d}t'\right) = \left[\frac{y_0}{y(t)}\right]^{\gamma}\left[\frac{P(t)}{P_0}\right]^{\gamma}. \tag{2'}$$

There are several difficulties associated with this way of evaluating the present value factor. First of all, we cannot predict future values of GWP (a problem which arises for every kind of discount procedure). Secondly, GWP is a problematic concept since, for instance, environmental degradation is not included. Thirdly, even if all these problems are solved, we have not considered the unjust distribution of income in the world. An expected rise in per capita income is accepted as a legitimate reason for discounting. But there are no average citizens of the world! Instead, we can expect that a middle-class North American who emits CO_2 today will be richer than a Bengali farmer will be 50 or 100 years from now, when the consequences from the emissions occur. This means that the same argument that is used for discounting costs in the future can be used to weigh costs that affect "poor" people higher than costs that affect "rich" people. A present value function that is general enough to take this aspect into account has been developed and applied to the problem of global warming (Azar, 1994b).

All this means that our method of discounting will not give an exact measure of how to estimate the present value of a cost or an income in the future, but we are convinced that this method is more correct than just applying a constant discount rate (which is the standard procedure), since our method explicitly deals with the reasons for discounting that have been discussed in the literature. Our expression for the present value factor is used in the Appendix where GED for emissions of CO_2 is calculated.

3. National environmental debt

3.1. Consistent calculations of national generational environmental debts

Should the pollution emitted by Swedish-owned factories located in Indonesia be included in the Swedish or the Indonesian GED? Should acid substances emitted in the UK but deposited in Sweden be included in the Swedish or the

British GED? There are four ways of delimiting calculations of national GED. [2] They are presented below and it is important to be consistent: i.e., not to mix them.

When calculating GED of a certain country (e.g., Sweden), one can (a) focus on all the negative environmental impacts on Swedish territory, independent of the nationality of those who caused the impacts and where the activities that caused the negative impacts took place (effect-related method). One can also (b) study all the negative effects on the global ecosystems (Swedish ecosystems included) following activities within Swedish territory independent of the nationality of those who caused the activities (activity-related method).

Furthermore, the Swedish national GED can be calculated by (c) studying all the environmental impacts that follow from consumption by Swedish citizens, as well as the production that is necessary for this consumption, independent of where the consumption, the production and the impacts take place (consumption-related method). Finally, the Swedish environmental debt can be given by (d) all the impacts resulting from production in Swedish-owned factories and the consumption of the goods that are produced in these factories, independent of where the production, the following consumption and the impacts take place (production-related method).

All four methods have their advantage and disadvantage, but they are often country-specific and we do not go into details here. We believe that the consumption-related method gives the most appropriate measure of a national GED, since those who finally utilise a good or a service also should pay for its negative effects (which can be seen as a consequence of the "polluter pays" principle). Today, this method is too complicated to use due to its high dependence on detailed statistics. Therefore, the activity-related method is often the most relevant of the useful methods. Finally, it should be noted that for the global GED, these four alternative methods coincide.

[2] This discussion is based on work by Karlsson (1992).

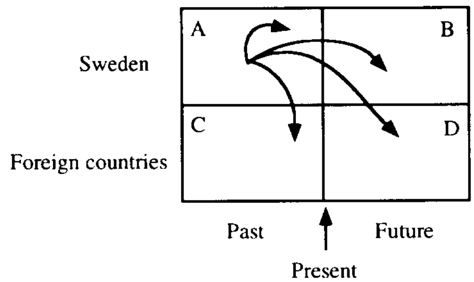

Fig. 4. The Swedish foreign and generational environmental debt for a specific activity. The Swedish foreign environmental debt of a past emission is given by the damage in areas C and D, the Swedish GED is given by the damage in areas B and D.

3.2. Foreign environmental debt and national generational environmental debt

National environmental debt can either stand for the environmental debt which a nation has to other nations, the *foreign environmental debt*, or the debt a nation has to future generations, the *national generational environmental debt*. In this paper we are only concerned with the latter. Fig. 4 illustrates the difference between these national debts (when the activity-related method is used for estimating the national GED). Suppose that a past activity in Sweden has caused damage in Sweden (A) and part of this damage will remain in the future (B). Suppose further that this activity has caused damage in foreign countries (C) and that part of this damage will remain in the future (D). Then the Swedish national GED includes the damage in squares B and D and the Swedish foreign environmental debt (FED) includes the damage in squares C and D.

Damage with short-lived impacts that have already occurred is not part of GED. But such impacts are part of the foreign environmental debt, provided that they have not been compensated for. Damage from past and present emissions of longlived greenhouse gases that have not yet been realised are, on the other hand, part of both the generational debt and the foreign debt.

3.3. Comparisons with the national public debt

In the Swedish debate following Jernelöv's evaluation of the Swedish GED comparisons were made with the national public debt. It has been argued that since Jernelöv's value for the Swedish GED was low compared with the Swedish national public debt, it was of less importance. But here it is important to distinguish between two aspects. The national public debt consists of loans from individuals to individuals via banks and financial and governmental institutions. This means that even if the government is in debt, there is no net debt between the present and the future generation. All future citizens will be born with a collective debt (the national public debt), but some of them (or citizens of other countries) as creditors. Therefore the national public debt is not a generational debt and quantitative comparisons between the national GED and the national public debt are not very relevant.

4. Total generational transfer

In the preceding sections we have presented a method for calculating GED, the generational environmental debt in monetary terms. In the Appendix the method is applied to the contribution to GED of past emissions of CO_2. But what are the limitations of this method and how should the value of GED be interpreted?

The method proposed to calculate GED requires monetary estimates of the value of the environment. Such estimates are difficult to make, and they were avoided by Jernelöv since he only considered restoration costs. [3] There are both practical and theoretical reasons for these difficulties. It is, for example, hard to predict which, if any, functions of an ecosystem will be lost if the concentration of a certain chemical is increased or a species goes extinct. For certain concentrations there might be situations where there is no detectable damage, but where a slightly increased concentration would cause severe impacts. These levels are often referred to as "thresholds". There is also often a considerable time delay between the human influence on the ecosystem and the manifest effects. Furthermore, ecosystems are multifunctional (e.g., a forest provides both shelter and food to its inhabitants).

Another point of criticism against the attempts to value environmental damage in monetary terms is that certain impacts are not comparable. Rawls (1971) proposed that economic optimisations should be performed in a certain order, where the right to life, health and liberty are the most important. And it is only when these rights are guaranteed to everybody that maximisation of consumption goods is desirable.

Furthermore, since our method assumes that comparisons can be made between the cost of restoration and the cost of damage, it implicitly assumes full substitutability between natural capital and human-made capital. It is important to note that this substitutability is limited (Daly, 1990). First of all, parts of the natural capital are life-supporting (production of food, protection against ultraviolet radiation, etc.) and cannot be substituted by human-made capital. Secondly, ecosystems are driven by sunlight and are self-organising whereas human-made capital depreciates if left to itself. Thirdly, there is an asymmetry between natural capital and human-made capital. Human-made capital is dependent upon natural capital for its build up, whereas the natural capital does not require any human-made capital. Finally, it is also true that the substitutability between different kinds of natural capital is limited.

In addition to this, it should be pointed out that restoring damage so that harm is not inflicted on future generations is morally different from compensating future generations for the damage. This has been stressed by Spash (1993, 1994).

This discussion has implications for the possi-

[3] This is only valid as a first approximation since restoration of damage often implies secondary changes to the environment which can be negative to future generations. The cost of these secondary changes must also considered when estimating the restoration cost.

bility of compensating future generations for environmental damage, as well as the attempts to measure sustainability through estimates of changes in human-made and natural capital. A limited substitutability between different forms of capital implies that some types of damage cannot be compensated for by a build-up of manufactured capital. The only way of respecting the rights of future generations in these cases is to take measures so that the damage does not occur: i.e., we should restore them. [4] In some cases where the damage is not restorable (e.g., loss of biodiversity, depletion of the ozone layer, etc.) future generations cannot be compensated.

All these limitations are important for the interpretation of GED. It implies that we should not aggregate GED with other intergenerational transfers [5] since such an aggregation implicitly assumes that full substitutability is always possible. Instead GED should only be considered as a monetary estimate of the burden of the environmental damage that we pass on to future generations.

GED can also be used when deciding appropriate policies for the future. Today much damage is not avoided or restored, since it is considered expensive. Calculations of GED make the cost that will fall on future generations visible.

[4] In this paper we only discuss past activities that will have negative impacts for future generations. As a policy recommendation for our present activities, this discussion implies that we should avoid causing such damage.

[5] There are both positive and negative intergenerational transfers. Examples of positive transfers are: build-up of manufactured capital and knowledge. The value of 1990 Swedish manufactured capital (the stock of fixed assets) was estimated at 500 billion US dollars (SCB, 1992). This value must, however, be modified since conventional methods of calculating the value of the stock of manufactured capital do not take into account the fact that some parts of it can be of no value to future generations. Examples of negative transfers, apart from environmental damage, are the accumulated depreciation of non-renewable resources, the increased risk of nuclear war following the production of plutonium in nuclear reactors (Swahn, 1992) or the spread of land mines in war zones (e.g., Afghanistan or Cambodia).

5. Concluding remarks

The concept of environmental debt has quickly become popular within the political debate in Sweden. The Swedish Ministry of Finance (1993) has stated that the environmental debt must not increase. This ambition is insufficient because it would make it possible to balance an enhanced greenhouse effect against restoration of acidified lakes. Furthermore, the long-term ambition should be to eliminate GED. The usefulness of the concept as a short run indicator of environmental policy can be questioned due to the great uncertainties in the calculations. However, this does not mean that GED is not useful. It has for a long time been possible to measure the ecological effect of societal influence on nature and establish that this influence is not sustainable. We have also been able to say that it is future generations that to a large extent will have to bear the burden of the way in which the present generation deals with nature. The generational environmental debt is an attempt to estimate this burden in monetary terms.

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Appendix: CO_2 emissions and the generational environmental debt

In this Appendix we calculate GED for anthropogenic emissions of CO_2 since the beginning of the Industrial Revolution. We use parameter values for climate change and its economic impact that are common in the literature, and insert them into our model for calculating GED. In order to make the calculations transparent, we use rough assumptions about the relation between emissions, atmospheric concentrations, temperature, climate change and damage. Introducing more details into the calculation does not necessarily lead to higher accuracy since uncertainties about both impacts and costs are significant. This means that the uncertainty range for the estimate of GED is wide, and would remain so even if more detailed equations were used.

We assume that sequestering carbon in biomass is the most cost-efficient method to prevent damage from past emissions of CO_2. The average sequestering rate (s_r) is assumed to be equal to 2.5 ton C/ha/year for the first 100 years; then it ceases. Roughly 300 Gton C have been emitted since the Industrial Revolution, of which 150 Gton C still remain in the atmosphere. We assume that biomass absorption of 1 Gton C reduces atmospheric amounts by 0.5 Gton C and ocean contents by 0.5 Gton C and that the excess of atmospheric CO_2 can be described by the following equation:

$$m(t, N) = \begin{cases} m_0 - s_r Nt/2 \\ \quad \text{for } t \leq T = 100 \\ m_T = m_0 - s_r NT/2, \\ \quad \text{for } T < t < 2T = 200 \end{cases} \tag{A.1}$$

Here m_0 (= 150 Gton C) is the present excess of carbon in the atmosphere due to past emissions of CO_2, m_T is the part of m_0 that remains in the atmosphere at time $t = T = 100$ years into the future and N is the number of hectares used for CO_2 sequestering.

A.1. Marginal benefit of reforestation

The benefit of restoration is given by the damage that is avoided. The cost damage function, $d(m(t,N))$, is assumed to be proportional to the anthropogenic contents of CO_2 in the atmosphere, i.e.:

$$d(m(t, N)) = km(t, N)y(t)/m_p \tag{A.2}$$

where m_p is the pre-industrial content of CO_2 in the atmosphere, $y(t)$ the gross world product (GWP), and k the fraction of the GWP that will be lost for a CO_2-equivalent doubling. We assume that no damage will occur for $t > 2T = 200$ years, which explains why no expression for $m(t)$ for $t > 2T$ has been assumed in Equation (A.1). Here we put $m_p = 600$ Gton C and $y(0) = 2 \cdot 10^{13}$ US dollars/year. There is considerable uncertainty about the value for k. Here we assume $k = 1.5\%$, which could be considered as a central estimate [Nordhaus (1993) assumes $k = 1.33\%$, Cline (1992) puts k in the range 1–2% and Ayres and Walter (1991) in the range 2.1–2.4%].

The present value of the damage is now given by integration of $d(m(t,N))$ multiplied by the present value factor [(Eqn. 2′, for a constant population and $\gamma = 1$, which corresponds to a logarithmic utility function which is not inconsistent with empirical studies (Blanchard and Fischer, 1989)]. We get:

$$\begin{aligned} d_{tot}(N) &= \int_0^{2T} d(m(t, N))V(t)\, dt \\ &= \int_0^{2T} k\frac{m(t, N)}{m_p} y(t) \frac{y_0}{y(t)} dt \\ &= \frac{ky_0}{m_p}\int_0^{2T} m(t, N)\, dt \\ &= \frac{ky_0}{m_p} M(N), \end{aligned} \tag{A.3}$$

where

$$\begin{aligned} M(N) &= \int_0^T m_0 - 0.5 s_r Nt\, dt + \int_T^{2T} m_T\, dt \\ &= 2m_0 T - 3s_r NT^2/4. \end{aligned} \tag{A.4}$$

The benefit of planting N hectare of land is given by the avoided damage: i.e., $B(N) = d_{tot}(N = 0) - d_{tot}(N)$. The marginal benefit of reforestation per hectare, $B_r^m(N)$, is obtained by taking the derivative of $B(N)$ with respect to N; we have:

$$B_r^m(N) = 3ky_0 s_r T^2/4m_p. \tag{A.5}$$

A.2. Marginal cost of reforestation

Estimates of the marginal cost of reforestation vary a lot [see Cline (1992) for a survey], and there are to our knowledge no studies available for $N > 10^9$ ha (approximately the area of the USA). It is reasonable to assume that the marginal cost will increase rapidly for very high values for N, since land will be scarce and reforestation will have to compete with other services that land can provide, e.g., food production. A crude expression for the marginal cost of planting an additional hectare of land is given by the following formula:

$$C_r^m(N) = c_1 + c_2 N^2, \tag{A.6}$$

where $c_1 = 2000 \cdot \text{US\$} \cdot \text{ha}^{-1}$ and $c_2 = 2 \cdot 10^{-14} \cdot \text{US\$} \cdot \text{ha}^{-3}$.

A.3. Degree of restoration

We define the degree of restoration (x) as the fraction of the damage that will be avoided:

$$x = \frac{d_{\text{tot}}(N=0) - d(N)}{d_{\text{tot}}(N=0)} = \frac{3 s_r T}{8 m_0} N. \tag{A.7}$$

A.4. Results

Restoration should be done until the marginal cost and the marginal benefit of restoration are equal. We get (Fig. A.1), for our parameter values, $N^* \approx 6 \cdot 10^8$ hectares, which makes the degree of restoration (x) equal to 38%. Total cost of restoration is given by integrating $C_r^m(N)$ from $N = 0$ to $N = N^*$ (area A), and the remaining damage by integrating $B_r^m(N)$ from $N = N^*$ to $N = N_2$ (area $B_1 + B_2$), where N_2 is given by Equation (A.7) for $x = 1$. The total GED is given by the sum of these two terms which is equal to $1.2 \cdot 10^{13}$ US dollars (of which the cost of restoration is $3 \cdot 10^{12}$ US dollars and the remaining damage is $9 \cdot 10^{12}$ US dollars). Swedish accumulated emissions of CO_2 are approximately 0.5% of global accumulated emissions. The Swedish GED is then equal to 60 billion US dollars.

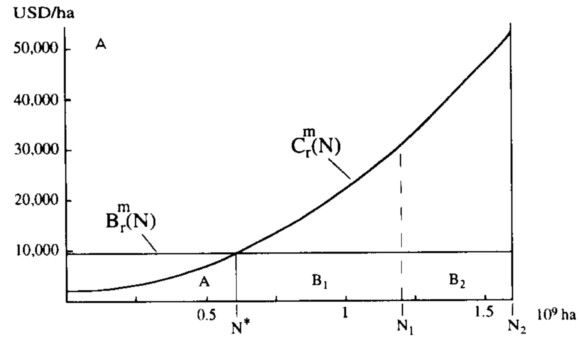

Fig. A.1. Marginal cost and benefit of reforestation. Restoration should be done until the marginal cost of restoration equals the marginal benefit (the intersection point in Fig. A.1). Area A is the total cost of reforestation and area $B = (B_1 + B_2)$, the cost of the remaining damage. If restoration is done until $N = N_1 = 1.2 \cdot 10^9$ ha, all emitted carbon will be absorbed in 100 years time, but in the meantime further damage will occur. The cost of this damage is given by area B_2. In this sense full restoration cannot be achieved. If $N > N_1$, damage will occur during an intial time period, but then the reforestation program will adbsorb the emissions of future generations. For $N = N_2 = 1.6 \cdot 10^9$ ha, the damage during the initial time period and the benefits during the rest of the time period cancel each other out. We define this as "full restoration".

A.5. Uncertainty range and sensitivity analysis

We know for certain that some gases, e.g., CO_2, CH_4, N_2O etc., have the property to absorb long-wave radiation and thereby to alter the radiative properties of the atmosphere. This is the greenhouse effect. We also know for certain that human societies have caused an increase in the atmospheric concentrations of these gases; in the case of CO_2 by approximately 25% since the beginning of the Industrial Revolution.

Uncertainties still exist about the impact that this change will have on the global climate. Using advanced and detailed simulation models, one can compute the expected change in the time-averaged mean global surface temperature for a CO_2-equivalent doubling to lie in the range 1.5–4.5°C, according to the Intergovernmental Panel on Climate Change (IPCC, 1990, 1992). This uncertainty range is considerable, but the uncertainty is even greater about regional impacts.

These uncertainties are further enhanced when climate impacts should be translated into economic impacts. What does this imply for the sensitivity of our results? First, we study changes in $B_r^m(N)$, the marginal benefit of restoration, and then we study changes in $C_r^m(N)$, the marginal cost of restoration.

Most economic studies of the greenhouse effect have focused on the impacts of a CO_2-equivalent doubling. These studies have then been used to estimate functional relationships between atmospheric concentrations of greenhouse gases and economic damage. There are to our knowledge no studies of the economic impact of the equilibrium climate change due to the present concentration of greenhouse gases in the atmosphere, and thus it could be argued that the present concentration of greenhouse gases will not give rise to any damage [some authors have even argued that the greenhouse effect initially could have a positive impact (d'Arge et al., 1982)]. In that case, GED would be equal to zero or even slightly negative, which would imply a positive transfer. This could be seen as a lower range value for GED.

A considerably higher value for GED would be obtained if we assume that damage will remain for a longer period than 200 years (which is reasonable considering that 15% or more of the accumulated CO_2 emissions will remain in the atmosphere for more than thousand years) or if we assume that the damage proportionality factor is much higher. Nordhaus (1994) has conducted an opinion poll on the economic impacts of climate change amongst leading natural scientists and economists and the highest damage estimate reported for a 3°C increase in the global annual average temperature change (which corresponds to a CO_2-equivalent doubling) was 21% of GWP.

For higher values of the damage proportionality factor or for a longer period of damage, the curve representing the benefits of planting trees (i.e., avoiding climate change) in our Fig. A.1. would shift upwards. If k, the damage proportionality factor, is larger than 7.5%, then the curve representing the benefits of reducing climate change will be shifted upwards above the curve representing the cost of reforestation, and the global GED would be given by the area under the latter curve. Thus, as a first approximation to the upper limit for GED we get $3.1 \cdot 10^{13}$ US dollars.

Now we could make the same analysis for the curve representing the cost of reforestation. If this cost would increase, GED would also increase, but never above the area under the curve representing the benefit of reforestation. If this curve is fixed, then GED is equal to $1.5 \cdot 10^{13}$ US dollars. It should be noted, however, that the uncertainty about the cost of damage is greater than the uncertainty about the cost of restoration. According to Broecker (1987): "we play Russian roulette with climate, hoping that the future will hold no unpleasant surprises. No one knows what lies in the active chamber of the gun."

One possible mechanism that can cause catastrophic impacts is that of a climate-change-induced acceleration of the loss of biodiversity, which is already occurring at a high rate. Predicting the social, ecological and economic impacts of this loss is impossible. Daily et al. (1991) write that "the elimination of natural populations and extinction of species is akin to popping rivets out of an airplane wing. While the wing might continue to perform minus a few rivets, no one with any sense would knowingly fly an aircraft undergoing such modification."

Thus, it could be argued that it is not possible to establish an upper limit for GED for CO_2 emissions.

In summary, due to the complexity in causal chains and delay mechanisms it is extremely difficult to give a narrow uncertainty range. The reason for making monetary estimates of GED in addition to physical indicators, even if the uncertainty range is wide, is that monetary measures have a strong influence on policy makers. In fact, the Swedish debate following Jernelöv's report on GED has resulted in greater interest in environmental problems in the Swedish Ministry of Finance (1993).

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