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The Economics of Climate Change and the Theory of Discounting

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Abstract - This paper confronts the theory of discounting with Climate Change economics. Standard discounting would give long-term damages a very low present value. On the other hand, low discount rates would imply more sacrifices for present generations, although future generations may be richer. And using multiple rates would lead to economic inefficiencies. The paper first shows that arguments favouring a low or zero discount rate in general are weak, even from an ethical point of view. It goes on by considering different arguments in favour of discount rates decreasing over time, and by recalling the argument that non-reproducible environmental assets should be given a value growing over time. Through the example of climate change, it finally shows that the latter argument not only implies that the costs of damages associated to Climate Change should not be underestimated, but also reinforce the legitimacy of using decreasing discount rates.

Keywords: Discounting; Climate Change; Environmental Economics

Introduction

The perspective of climate change caused by human action, a problem that is characterised by a very long time lag between the moment our actions take place and their possible consequences on the climate, has given rise to renewed interest in the discount theory, and the legitimacy of its use in an inter-generational context.

This paper will be limited to discussion of the present value of future climate change. The dilemma is simple: economic theory holds that a single unified discount rate is a necessary condition for the efficient allocation of resources in a global economy. It is therefore not really advisable, *a priori*, to use a specific rate for analysis of climate change. If a "standard" discount rate (between 5% and 10%) is used, the economic analysis will apparently be able to assign only a very low present cost to eventual future damages, even very large (discounting at 8% over 100 years comes down to dividing 2,200), and will in conclusion legitimate inaction. If, inversely, the general discount rate is lowered, it is the equivalent of saying that the present generation must invest much more– and in all domains: we should therefore consume less and save more to benefit descendants presumably richer than we are. Both of these conclusions are contrary to common sense.

To begin with, I will demonstrate that most of the arguments made in favour of constant low discount rates for the sake of future generations are weak.

Secondly, I will look at two types of answers proposed as solutions to the dilemma: those which plead in favour of declining medium and long-term discount rates, and those which

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plead for valuation of certain natural assets at a rate which rises over time at the same pace as the discount rate. I will show that these arguments are mutually supporting.

Thirdly, I will show that uncertainty as to future outcomes could justify both adoption of a rate that decreases rapidly with the time frame, and "effective discounting" of natural assets, in the sense suggested by Fisher et Krutilla (1975): the growth rate of the value of these assets must be kept slightly lower than the discount rate.

Fourthly, I will try and apply these arguments to the economic analysis of Climate Change - and show how this exercise may reinforce the points made.

Lastly I will draw from these reflections on the discount rate some conclusions as to the economic analysis of Climate Change, and its limitations.

1 - Arguments in favour of low rates

The Second Assessment Report of the IPCC devoted a whole chapter to the question (Arrow *et al.*, 1996), introducing a fundamental separation between "descriptive" approaches which endeavour to deduce a discount rate from the markets, and the "prescriptive" approaches, which generally make a plea for discount rates that are markedly lower than the former, and go as far as rejecting the legitimacy of discounting.

Arguments in favour of low rates generally pursue the following line of reasoning:

(1) Demonstrate the normative domination of the social rate of preference for the present, over the marginal rate of return on private investment;

(2) Demonstrate that individuals are "isolated" by markets, and cannot express their real preferences with respect to future generations;

(3) Plead for a pure preference for the present of value zero in an intergenerational context, on the basis of ethical arguments.

These three arguments will be examined in turn. Then I will examine the quite different argument advanced by Martin Weitzman, in favour of a lower discount rate because of the environmental damage linked to economic growth. (**4**)

1.1. The social rate of time preference

In the world of Irving Fisher (1930), the time preference rate of consumers and the marginal rate of return on investment are equal. In the real world, the presence of taxes and risks is usually considered as creating a difference between these two rates. Which of these two rates should be used as a discount rate? Each has its advocates.

For one group, if a project or policy is to be financed by further levies on consumption, this project or policy must be analysed simply in terms of the social rate of time preference. If its net present value is positive, the project deserves to be undertaken. For the other group, as soon as means are levied, they must be spent as efficiently as possible and this as much for the sake of future generations as for that of present generations. Cline (1992) and his critics (Birdsall and Steer 1993, Nordhaus 1994) illustrate these opposite views in the case of Climate Change mitigation analysis.

We will not enter here the detail of that debate, often darkened by some confusion between the normative value of discount rate for public investments - then defining the size and the economic role of the State - and its normative value for public policies, which may entail private as much as public investments.

We will simply admit here that the consumer's time preference is the necessary criterion when it is a matter of assessing the advantages of foregoing immediate consumption in favour of future consumption, the aim of the economy being welfare derived from consumption, in turn derived from production. But this does not mean we should not take into account[2] the possible crowding out of private investment from the public policy in question, via a "shadow price" of capital.[3] Nor does it mean that the consumer time preference is independent of the productive capacity of the economy; on the contrary, they are strongly interdependent, as Irving Fisher (1930) recalls us, using the following desert-island paradigm. Imagine a desert island where some sailors have been shipwrecked, each with a given number of biscuits ("*pounds of hard-tack*"), and no prospect of ever improving his lot. Therein lies their only real income, and they have no hope of ever increasing it. The only possible variation in their income flows– i.e. in the consumption of biscuits– is the possibility of changing the moment at which the product is consumed. In such a community, the interest rate as a function of biscuit will necessarily be zero, because, by definition, removing one biscuit from present consumption can only lead to an equivalent increase in future consumption. *"In other words, the rate of return over cost is zero. Since this rate must equal the rates of preference, or impatience, and also the rate of interest, all these rates must be zero also."*

There can be no doubt that under these circumstances the rate of return is zero. But what about the interest rate? No potential lender could obtain interest greater than zero on an advance, seeing as the only way a borrower could pay back would be to take the repayment out of the initial stock of biscuits. For why borrow 100 for immediate consumption, if 105 must be paid back the following year? You might as well take 100 from the supply, which the following year is diminished by 100, not by 105.

Does the same hold true for time preference? Yes, says Fisher. Assume that one sailor prefers one certain consumption profile to another: he has only to apportion his stock of biscuits in the way he likes best. Does he prefer a biscuit eaten now to a future biscuit? He can draw on his stock, up to the point where his desire for present consumption precisely balances against his desire for future consumption, up to the point where the two are equal. A prodigal consumer and an avaricious one would not have the same consumption profile of course, but for one and the other a biscuit today would be worth precisely as much as a biscuit in a year's time.

In such a case the investment opportunity dominates the interest rate, forcing it to be zero. Other cases that are representative of the same domination can be imagined, with negative interest rates (just replace the inalterable biscuits with figs, half of which rot each year, which induces an interest rate of -50%) or positive rates (in this instance the biscuits are replaced by trees or sheep, capable of production and reproduction at a certain rate). But in actual life the investment opportunity does not dominate the interest rate because there are an infinite

[2] Arrow (1995) and Fankhauser (1995) consider that in the case of Climate Change only the effects on consumption are important. For a discussion of this argument, see Philibert (1996).

[3] The method recommended by Cline is in my view the most complete one in theory, for reasons that I will not go into here. However it could make sense, for simplicity's sake, to opt for the method using the weighted average of the two rates, even though it is theoretically wrong, as shown by Feldstein (1972).

number of opportunities: in this situation, no increase or fall in real income over time can occur without inducing a change in the rate of return over cost: "*The result is that the rate of impatience influences the rate of return quite as truly as the rate of return influences impatience. (...) The more we invest and postpone our gratification, the lower the investment opportunity rate becomes, but the greater the impatience rate; the more we spend and hasten our gratification, the lower the impatience rate becomes but the higher the opportunity rate.*"

In a world where risk and fiscal measures create a wedge between marginal rate of return on private investment and the social rate of time preference, we may accept the normative domination of the latter, if we do not forget its close interdependence with the former.

1.2. The "isolation paradox"

John Broome (1992) summarises the argument developed by Marglin (1963) and Sen (1961, 1967):

"*Saving for a future generation is partly a public good. Each person's saving is valued by others. There are two reasons for this. The first applies even if everyone cares only for her own descendants. In the nature of things, not all the benefit of my savings will be received by my own descendants. Inheritance taxes, amongst other things, spread them around. So when I save, I benefit other people's descendants, and those other people (my contemporaries) value that. The second reason applies if people have a wider concern for posterity beyond their own descendants. In that case, even the part of my savings that goes to my own descendants is directly valued by other people.*

"But public goods are always undersupplied by the free market. The free rider problem means that people's individual savings will be less than the optimum level: less than the level individuals would themselves choose".

Whether it is because inheritance taxes spread people's savings around to a larger number of "heirs", or simply because many members of the present generation leave something to their own heirs, the consumption of future generations in both cases is seen as a public good by the present generation. And yet the theory shows that the market naturally undersupplies public goods.

Here Broome implicitly takes the view that public goods are produced through contribution, by only likening savings and investment to the voluntary contributions made by each person to a share of that public good: the wellbeing of future generations. In this context, people match the marginal cost of producing public goods with their own marginal willingness to pay. And yet the optimal level of public good production would come from matching the same marginal cost of production with the marginal will to pay of all (a condition made by Bowen, Lindhal and Samuelson). The more the people the greater the difference. This sub-optimal state results from a lack of co-ordination, which does not at all presuppose that people have distinct preferences.

However, the theory that the free market always undersupplies public goods does not necessarily apply here. The "public good", which for the present generation is the wellbeing of future generations, is itself made up of private and public goods. The consumption of private goods by future generations depends on a great many factors, particularly investment by the present generation and successive generations in between. This investment could be long-term, as Lind (1964) illustrated with his model of overlapping generations. We should also bear in mind that many economic agents would like to leave goods to their heirs, and that most of them do not choose, and do not know, the moment they will die. In other words, producing "public good", the wellbeing of future generations– in so far as this wellbeing depends on the consumption of private goods– depends on mechanisms that have not been shown to lead necessarily to a sub-optimal state. On the contrary, if the economic growth continues faster than the demographic growth, future generations will be richer.

The greater foreseeable wealth of future generations is the fundamental objection that Gordon Tullock (1964) opposes to Marglin (1963). In general only those whose income is below the average level are considered as possible recipients of charitable giving. In this case, an altruist must carefully weigh the effects of a donation given to a poor person today, rather than to a member of future, richer generations. In any event, according to Tullock "*collective savings of the type Marglin proposes clearly tax the poor to help the rich*". In other words, it is not certain that our great-grandparents would have tightened their belts more if they had known what our level of material wealth would be.

Baumol (1968) follows the same line: "*In our economy if past trends and current developments are any guide, a redistribution to provide more for the future may be described as a Robin Hood activity stood on its head - it takes from the poor to give to the rich. Average real per capital income a century hence is likely to be a sizeable multiple of its present value. Why should I give up part of my income to help support someone else with an income several times my own?*" But he goes further: "*However, this does not mean that the future should in every respect be left to the mercy of the free market. There are important externalities and investments of the public goods variety which cry for special attention. Irreversibilities constitute a prime example. If we poison our soil so that never again will it be the same, if we destroy the Grand Canyon and turn it into a hydroelectric plant, we give up assets which (...) when once destroy'd can never be supplied. All the wealth and resources of future generations will not suffice to restore them. Investment in the preservation of such items then seems perfectly proper, but for this purpose the appropriate instrument would appear to be a set of selective subsidies rather than a low general discount rate that encourages indiscriminately all sorts of investment programs whether or not they are relevant.*"

Here is the point: the wellbeing of future generations also depends on their consumption of, or access to, a certain number of public goods, including many environmental goods. And of course it seems that the theory of public goods can be applied to the production of these goods in the future as well as in the present. Furthermore, the organisation of efforts to mitigate climate change presents the same logical structure as the isolation paradox: it is an extension to *n* agents of A. W. Tucker's famous prisoner's dilemma. All individuals informed of the threat of climate change may want to protect future generations from this threat, and to this end may be ready to sacrifice some immediate consumption, that for this purpose I will call "investments" (even if it is a question of one day riding a bicycle instead of driving a car: this sacrifice of immediate convenience gives future generations a little less climate change).

Any reasonable person would, however, be aware that his/her small individual sacrifice would make very little difference to the overall threat from climate change. It is generally considered that no nation, except perhaps the United States, weighs heavily enough in the world total of greenhouse gas emissions to hope for a direct return on its own mitigation initiative. Each nation, in fact, hopes that the other nations will reduce their emissions, and so hopes to get out of having to make any effort itself. This state of affairs inevitably leads to a non-optimal overall result, unless a mechanism is put in place to ensure that every nation makes an effort. Then everyone will benefit from the effort made by others. This is the fundamental justification for international conventions such as the United Nations Framework Convention on Climate Change and its extension, the Kyoto Protocol, on the condition of course that their measures are indeed implemented.

What is true for nations is all the more so for individuals: no-one can inflict on himself all the sacrifices needed to mitigate climate change, if it means doing so in a rational way within an ethics of "consequentialism" (anyone obeying Kant's categorical imperative would naturally choose to use a bicycle, even if he/she were the only one). In the same way that nations would act differently depending on whether the Convention existed or not, so, in their daily behaviour, individuals would not necessarily indicate their approval of instituting a mechanism forcing everyone to take action. The discount rate on the market would not reflect people's willingness to act on behalf of future generations. Their willingness can only be revealed through a process of deliberation and democratic decision, however imperfect. Therefore, there is a definite lack of market co-ordination for this particular category of investment. But this does not imply that we must lessen the discount rate and invest more in general. A more specific way to deal with the problem seems necessary.[4]

1.3. Pure time preference

Since the end of the nineteenth century the idea of discounting utility itself, that Harrod (1948) was apparently the first to call "pure preference for the present", is an idea that disturbs, intrigues and fascinates.[5] The condemnations issued by Pigou (1920), Ramsey (1928) and Harrod (1948) are proverbial. Closer to us, Solow (1992) does not try to hide his predicament. The pure preference for the present seems to be necessary in order to avoid excessive sacrifice by the present generation for the benefit of following generations, and yet to many it seems irrational, when considering the utility of the individual faced with present choices, and morally unacceptable when considering the utility of future generations. What right has the present generation to place a lower value on the utility of future generations than on its own? Inversely, without a pure preference for the present, the discount rate could fall to a level so low that it would imply very high investment by the present generation.[6] But the latter, presumably less well off than succeeding generations, due to economic growth, would be unfairly penalised. Hence the dilemma: is it fair to reject the preference for the present, or is it fair to avoid asking the poorer generation for more sacrifice, by explicitly attributing less weight to the utility of future generations?

I will start with a suggestion by John Rawls (1971) for dealing with this dilemma: "*It is also possible to vary the accumulation required by adjusting the parameters in the postulated utility function*". If a purely "descriptive" position, in which consumer preferences are simply observed, is left behind and a more "prescriptive" position adopted for ethical reasons, it is of course logical to give the pure time preference a nil value (as did Cline, 1992), but in this case

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[4] A more complete analysis of the isolation paradox can be found in Philibert (1998).

[5] It is seemingly since Arrow (1966) that the discount rate, or rather the "social rate of preference for the present", has acquired its modern physiognomy where SRPP = $\rho + \theta.g$ (standard notation), the sum of the pure preference for the present and the product of per capita income growth multiplied by the absolute value of the income-elasticity of marginal income utility, a product that Arrow (1995) calls the "wealth effect".

[6] Arrow (1995) reiterates this argument in favour of the pure preference for the present in an economy assumed to be stable, he attributes to Tjalling Koopmans. However this investment would yield a bigger economy, and this contradicts the basic hypothesis. This "growth" should be accounted for by the "wealth effect." It is the most powerful argument against low discount rates – but not necessarily in favour of pure time preference.

the income elasticity of marginal income utility should not be observed, but chosen– as it is no longer a question of utility for the same agent, but of an interpersonal comparison. In this way the potentially greater wealth of future generations can be explicitly accounted for. As recognised by Arrow *et al.* (1996), "*Just as the choice of the rate of pure time preference (ρ) has important implications for intergenerational equity (...), so does the choice of the elasticity of marginal utility (θ). The more weight the society gives to equity between generations, the higher the value of θ (...)*".

How should this coefficient be chosen? Concern for equality might suggest an infinite value: rendering the poorest even poorer could in no way be justified by enrichment of the richest. But this proposal leads to an absolute indeterminate result: investment becomes nil, and economic growth as well... and the wealth effect, to which the discount rate is reduced by the zero level of the pure preference for the present, is the indeterminate product of zero multiplied by infinity. The error is manifest: the discount rate determines the level of investments, which are intended not only for the wellbeing of future generations, but also for the future wellbeing of the present generation. In addition, economic growth itself also depends on the level of investment: the result of the multiplication thus affects in turn one of its terms. Thus it does not seem possible, using a normative approach, to proceed otherwise than by successive adjustments, using growth models, to determine by correlation the desired rate of economic growth and an acceptable investment rate. Or, more simply, if the observed investment rate[7] seems acceptable from the standpoint of future generations, and the pure preference for the present is set at zero, then it appears to be legitimate to adjust the income elasticity coefficient of marginal utility of income so that the product when multiplied by the expected rate of growth in per capita income is equal to the currently applicable discount rate. Hence this paradox: a half-prescriptive approach leads away from the outcome suggested by a descriptive approach, but a fully prescriptive approach leads back to it, because ultimately, under an ethical approach, there is no reason to refuse the discount rates currently in use, as long as they are compatible with progressive improvement – in any event absence of regression – in per capita income as time goes on. It is indeed quite striking that in his analysis of Rawls' thinking on the fair savings principle Kenneth Arrow (1973) in no way refers to the pure preference for the present, but exclusively to the decreasing marginal utility of income, to explain the fact that the present generation limits the extent of its efforts granted for the benefit of generations to come: "*(...) if we have any regard at all for the future generations (as justice demands) and if the gain from waiting is sufficiently great, then we will want to sacrifice some for the benefit of future individuals even if they are, to begin with, somewhat better off than we are. We will not do this indefinitely; this is usually formalized by assuming that they and we have diminishing marginal utility, so that at some point the gain in commodity terms ceases to be a gain in utility terms*".

1.4. An "environmental" discount rate

Martin Weitzman's argument (1994) is profoundly different in nature. His point of departure is to link the level of economic activity with its effects on the environment. A marginal investment that creates additional growth also entails the need to increase environmental spending so that the quality of the environment– here taken as an externality– remains at least constant. This reduces the yield– for the community– of private investments. Martin

[7] Arrow (1995) recalls Ramsey's classical result (1928) that the optimal savings ratio is 1/θ.

Weitzman shows that a simple formula can account for this "environmental drag" effect by linking the social discount rate *r*, to the marginal return on investment *i*:

$$r = i(1-\gamma)$$

in which γ represents a "coefficient of environmental drag" which is itself a function of the percentage of environmental spending in the national product Z, and of the elasticity of enhancement of the environment in relation to this spending, E, as follows:

$$\gamma \equiv Z\left(1+\frac{1}{E}\right)$$

Here Weitzman is pleading not only for a social discount rate that is lower than the marginal return on private investment– even in an economy "without distortions"– but also for a rate that is degressive over time: the fraction of revenue devoted to environmental protection should logically grow over time with the level of development, both by an increase in the preference for the environment, and because "*greater economic activity typically results in disproportionately greater environmental degradation through pollution*". Weitzman feels however that it is hard to evaluate how the efficiency of environmental spending may vary over time.

This line of reasoning is fairly convincing– but the correction of the discount rate minimal. Weitzman estimates the value of E at between ½ and 1, and the proportion of environmental spending in GDP in 1990 at 2.1%, which would lead to setting the environmental resistance factor at between 4% and 6%. Recalling that environmental spending in the United States was only 0.9% of GDP in 1972, rose to 2.1% in 1990, and is estimated by the Environmental Protection Agency to reach 2.7% in 2000, Weitzman notes, however, in conclusion that this coefficient could rise rapidly in the future. One may wonder, above all, if the actual level of environmental spending really fits the hypothesis of a constant environmental quality.

2 Arguments in favour of a rate declining over time, and in favour of increasing valuation of natural assets

A declining discount rate is the necessary corollary to the slowing down of economic growth, that some hold to be inevitable due to the limitations of the planet itself (**2-a**). In addition, a spread between the discount rate and the pace of economic growth raises insurmountable problems in the long run (**2-b**). Finally, the absolute rarity of certain natural assets warrants that their relative value rise progressively (**2-c**). These arguments are more or less equivalent (**2-d**), and can follow Weitzman's modelling (1994).

2.1. The limitations of our planet

If the hypothesis of physical limits to economic growth– a "carrying capacity"– is accepted, then the growth rate is not constant, i.e. growth is exponential only for a "brief" interval of time. In fact growth follows a logistic curve (an "S" curve), with a deceleration leading sooner or later to a steady state of the economy in the long run. It would therefore be appropriate to adopt discount rates that fall over time.

On this consideration, Sterner (1994) suggests to replace the habitual formula $1/(1 + r)^t$ by the following: $r/\{r/c + (r - r/c)(1 + r)^t\}$, in which the parameter c represents the ratio of the maximum gross world product (GWP) ("carrying capacity") to current GWP.

Thomas Sterner (1994) multiplies GWP by ten to obtain a valuation of the planet's "carrying capacity" which would allow a world population doubled in size to attain on average the current income level of residents of industrialised countries, in 250 years.

Here it is interesting to compare the present values of a monetary unit at different time horizons, depending on whether growth is steadily exponential (a constant discount rate of 3%) or logistic. One unit in 20 years is worth 0.554 today in the first case and 0.598 in the second: a small difference for the evaluation of many projects in this time frame. The same unit in 100 years is worth 0.052 under exponential growth, and 0.147 under logistical growth. In 250 years it is worth only 0.0006 in the first case, and 0.101 in the second. The present value of future values beyond this horizon practically disappears with exponential growth ($\pm 10^{-13}$ in 1,000 years, $\pm 10^{-33}$ in 2,500 years), while it levels out indefinitely at 0.1 with logistical growth.

Martin Weitzman (1999) protests against this pessimistic vision of the Earth's "carrying capacity", arguing that "*the reason that we keep on getting ever more units of output per unit of inputs is because of "technical progress", which is just a synonym for human ingenuity or inventiveness. It is technical progress that, by warding off diminishing returns, prevents capital productivity from falling over time*". And he pursues: "*Global warming might cause a rise in sea level, which in turn could cause low-lying cities to be flooded if they were not walled off and pumped out. But if and when this event happens two centuries or more in the future, it's not such a big deal because a very modest savings program started now would accumulate enough bricks and metal and so forth that we could easily afford to build the walls and pumps and everything else we would need if the underlying trend of the real rate of interest remains about the same*".

However, even if one shares Weitzman's optimism as to human ingenuity and continued economic growth[8], it is not certain that this growth justifies long-term discounting at a high rate. Such discounting supposes continual and total reinvestment, at the same rate, from generation to generation, as was seen by Lind (1990). "*The logic which serves to justify discounting in the benefit-cost framework is that a project should be adopted if the beneficiaries from the project could more than compensate the losers, i.e., if everyone could, at least hypothetically, be made better off. The problem with this criterion, when it is applied over many generations, is how to implement and guarantee such intergenerational transfers. For example, suppose the current generation were to adopt policies which would greatly reduce its cost of producing energy but which would create significant environmental costs 200 years hence. On the grounds of intergenerational equity, suppose the present generation would like to share the gains from adopting such a policy with the future generation. According to the logic of benefit-cost analysis, if the discounted future costs were less than the current benefits (when discounted at the marginal rate of return on investment), a part of these current benefits could be set aside and invested and reinvested for 200 years. These growing earmarked savings would provide the future generation with more than enough extra*

[8] The quotation above belongs to the first part of that text, which was first presented at a Resources for the Future/Energy Modelling Forum Workshop in November 1996 under the title "Just Keep Discounting". Its strength is somewhat mitigated by the second part (the "but" part…) of the same text, which was written afterwards, in full consistency with Weitzman (1998).

resources to cover the environmental costs that it will incur. Given this logic, it is the rate of return on private capital that is the appropriate discount rate.

"There are problems which make such a trade impossible to implement even if the present generation chose to do so. First, this would require a net increase in investment in the economy that would be sustained through reinvestment for 200 years. Aside from the fact that we do not have the economic policy tools necessary to increase net investment in the economy by some desired amount, more importantly, it would be necessary to commit each subsequent intervening generation to the maintenance of that policy. There is no way of doing this since the intervening generation might have strong incentives to increase their own consumption at the expense of the future generation. In the absence of the possibility of intergenerational compensation, the benefit-cost logic is much less compelling".

On top of this "policy" difficulty, there is a logical challenge, due to the gap between the discount and growth rates, as will be seen with Ari Rabl.

2.2. The impossible compensation

Ari Rabl (1996) suggests considering an equation giving the future value F at time $t = N$, of a project generating a net benefit B at time $t = 0$, and a single cost C at time $t = N$. If the present value P is written as $P = B - e^{-rN} C$, as a function of the discount rate r, than the future value is expressed as $F = e^{rN} B - C$. Rabl writes:

"*We see that there is an inconsistency if any rate r greater than the GNP growth rate r_{gro} is used for a sufficiently long time: eventually the annual benefit $re^{rN} B$ becomes larger than the entire GNP– clearly an absurdity*".

A discount rate that is the result of the sum of a pure preference for the present with a "wealth effect" that coincides with the economic growth rate, for Rabl who assumes a logarithmic utility function (income elasticity of the marginal utility of income equal to -1), incurs the risk of this absurdity when the long term comes into play.

According to Ari Rabl the origin of this absurdity should be sought in the twin wellsprings of the rate of interest, "*reflected by the two components of the discount rate: there is the money people pay to be able to consume now rather than in the future, and there is the gain from economic growth. Only the latter represents creation of wealth; the former merely redistributes it. Assuming constant rates, the gain from growth continues forever. But the money from redistribution is a limited pool, essentially paid by each generation for its own consumption preferences. It would be an error to consider it as income forever*".

The limits of this redistribution are not clearly defined, because generations overlap as they follow each other, and because loans cover different time spans. A loan redistributes money for a certain period of time, and the redistributive contribution of this loan at the social discount rate ceases when it comes to an end. The time preference component of the discount rate therefore cannot be relied upon to compensate for harmful effects beyond the horizon of the duration of loans currently running when it is decided to undertake a project. "*Within the present generation the conventional rate is justified by the existence of a market of borrowing and lending activities which expresses the preferences between current and future consumption. There is no intergenerational market, and only the growth component of the discount rate is relevant for a cost-benefit analysis from the point of view of future generations*".

As a consequence Rabl (1996) proposes a two-tier discounting procedure, using the conventional rate for a short period– 30 years, for example– and then a reduced rate for intergenerational effects. This reduced rate would be equal to the hoped-for rate of long-term economic growth.

Ari Rabl's reasoning is powerful, but fraught with problems. First of all it poses a problem of temporal consistency: the value of a given capital *in 2030*, naturally equal to the discounted sum of its future net benefits, will vary depending on whether it is calculated in 2030 or in 2000. It should be noted that this problem did not arise with Sterner's proposal, apparently similar, but based on other considerations. The hypothesis of a non-constant rate is legitimate if growth slows down; but the hypothesis of a rate that varies with the time gap between the date of analysis and the date of the event analysed is truly problematic. This already bothered Ramsey in 1928: *" (...) assuming the rate of discount constant (...) is the only assumption we can make, without contradicting our fundamental hypothesis that successive generations are actuated by the same system of preferences. For if we had a varying rate of discount - say a higher one for the first fifty years - our preference for enjoyments in 2000 A.D. over those in 2050 A.D. would be calculated at the lower rate, but that of the people alive in 2000 A.D. would be at the higher."* Solow (1999) shares this concern: "*Unless the discount rate is constant, the policy path is subject to 'time inconsistency' ".*

But in fact Rabl concurs with Sterner in that the problem he raises exists only if the future costs to be compensated are very high, and therefore cease to be marginal. The solution to the problem must integrate these costs in calculating growth, and the discount rate must be revised as a consequence.

But is it possible to conceive of non-marginal environmental costs, i.e. of the same order of magnitude as GDP? Undoubtedly yes, as will be seen now, if we pay attention to the irreplaceable nature of Nature.

2.3. Valuation of natural assets

2.3.1. The American school

John V. Krutilla (1967) advances two reasons for attributing a progressively rising value to certain environmental resources: "*There is likely to be an asymmetry in the implications of technological progress for the production of goods and services from the natural resource base, and the production of natural phenomena which give rise to utility without undergoing fabrication or other processing. In fact, it is improbable that technology will advance to the point at which the grand geomorphologic wonders could be replicated, or extinct species resurrected. Nor is it obvious that fabricated replicas, were they even possible, would have a value equivalent to that of the originals. To a lesser extent, the landscape can be manufactured in a pleasing way with artistry and the larger earth-moving equipment of today's construction technology. Open pit mines may be refilled and the surroundings rehabilitated in a way to approximate the original conditions. But even here the undertaking cannot be accomplished without the co-operation of nature over a substantial period of time depending on the growth rate of the vegetal cover and the requirements of the native habitat. Accordingly, while the supply of fabricated goods and commercial services may be capable of continuous expansion from a given resource base by reason of scientific discovery and mastery of technique, the supply of natural phenomena is virtually inelastic. That is, we may preserve the natural environment which remains to provide amenities of this sort for the* *future, but there are significant limitations on reproducing it in the future should we fail to preserve it*".

This probable inability of technical progress to fabricate or replicate certain environmental goods is not without consequences for the evolution over time of the prices to be assigned to environmental goods: "*If we simply take the effect of technological progress over time, considering tastes as constant, the marginal trade-off between manufactured and natural amenities will progressively favor the latter. Natural environments will represent irreplaceable assets of appreciating value with the passage of time* ".

Another reason for assigning a rising value to environmental goods is the greater preference for the environment, which according to Krutilla stems from learning through practice. The two reasons can be joined of course.

J. V. Krutilla returned to this idea and developed it on several occasions, singly or in collaboration with A. C. Fisher and/or C. J. Cicchetti. One of their hypotheses is that while the benefits of preservation increase over time, those of development diminish, as all investment "freezes", as it were, a technique in a given state of advancement, while the technology continues to progress.

Fisher, Krutilla and Cicchetti (1972, 1974), then Fisher and Krutilla (1974, 1975) step by step draw up a new model for calculating the net present value of any given investment. Assuming that net benefits (after deduction of variable costs) and costs of an investment, discounted at a positive rate *i*, are constant over an infinite period of time, the net present value of the investment, designated as NPV_d would be simply established as follows:

$$NPV_d = [D_t/(i)] - C_0 - [P_t/(i)]$$

where D_t represents the annual value of the net benefit, C_0 the initial investment cost and P_t the annual net cost value, in this instance the benefit of preserving the environment in the absence of this investment.

Using Fisher's and Krutilla's hypotheses of the benefits of development diminishing at a rate *g*, and the benefits of preservation rising at a rate *r*, the net present value becomes:

$$NPV_d =[D_t/(i+g)] - C_0 -[P_t/(i-r)]$$

Later Porter (1982) showed that the sign of the NPV depends on the discount rate *i*. A very low rate will ensure the predominance of the exponential benefits of preservation, and the present net value will be negative. Inversely, a very high rate will ensure the predominance of the initial investment cost over the discount benefits of development, and the present net value will once again be negative. However, if the rate lies in between, the present net value will be positive, and the investment will be accepted.

But what values should be assigned to the rates *g* and (most importantly) *r*? Fisher and Krutilla do not give us any leads. In their presentation of the Porter model, Hanley and Spash (1993) observe that "*the growth rates g and r can be difficult to estimate and may be unstable over time*". Returning to the work of Krutilla and Fisher and interpreting it in turn, the same authors list the reasons for expecting the benefits of preservation to rise: "*First, because of increasing relative scarcity. As the area of tropical rain forest declines, each remaining hectare becomes more valuable and WTP increases due to the law of diminishing marginal utility. Second, because information on the importance of ecosystems' structure and diversity is increasing and being more widely dispersed over time, people become better informed; thus aggregate global WTP to preserve natural resources, such as rain forests, is likely to increase. Finally, as real incomes rise, demand for environmental goods and services may* *also increase*". It could be inferred from this that the rate of valuation of natural assets includes a component tied to the rate of their destruction, a second component related to the increase in preference for the environment, a third one being the rate of real income growth.

Desaigues and Point (1993) for their part explain that the total availability to pay, allowing evaluation of environmental goods, rises at a rate h+v+vh, expression in which h represents the rate of variation in "quantities" and v the rate of variation in prices. How can these values be determined? Desaigues and Point imagine a reference to "*a series showing for example the rising number of visits to protected natural sites (information on h) and to data containing information on the evolution in the maximum price that individuals assign to certain elements of the natural heritage (information on v)*".

Meanwhile, Arrow and Fisher (1974) and Claude Henry (1974) put forward the notion of a "quasi-option" value associated with each decision made with a pledge not to undertake irreversible development. As explained by Arrow and Fisher, "*essentially, the point is that the expected benefits of an irreversible decision should be adjusted to reflect the loss of options it entails.*"

This "quasi-option" value, while not necessarily linked to environmental issues, is however necessarily associated with an irreversible phenomenon. " *The dynamic model is relevant only if the pollution is in some sense irreversible, as is the extinction of a form of life, or the destruction of a unique geomorphological phenomenon*", explain Arrow and Fisher (1974). And the authors pursue with another example: "*the same reasoning would apply to cumulative "macro" environmental effects, such as the increasing concentration of carbon dioxide in the global atmosphere, with its attendant climatic changes, as predicted by some ecologists*".

To conclude with this "American" literature, what these authors have in common, it could be said, is that they seek primarily to evaluate consumer wellbeing. They study how the utility functions of economic agents are affected by damage to the environment. They therefore have no preconceived assumptions as to the growth rate of environmental values. According to these authors they should be estimated in relation to the time trends observed in environmental preference, and, perhaps, to the rate of destruction of natural resources. No potential link is evoked between the discount rate and the rate of appreciation of the benefits of environmental preservation.

2.3.2. The French school

Marcel Boiteux (1976) defends discounting on another ground: that of opportunity cost. In this view, all resources available in strictly limited quantity, i.e. that the economy cannot produce or replicate, must according to him be assigned a value that increases at a pace equal to or greater than the discount rate:

"*It is true that discounting diminishes all future values when unit prices are regarded as being constant, or varying little, over the years. The fact is that many people who apply discounting as one might follow a cooking recipe forget a fundamental aspect of long-term studies: the variation of relative prices with respect to each other. And yet it is quite clear that with constant money, prices of electronics will decrease along with technical progress, and salaries will increase with higher standards of living. The prices of products that are widely extensible because of human activity will decrease, and the prices of scarce resources will increase.*

”*In particular, all economic models show that in a growing economy the prices of resources available in strictly limited quantities should be assumed to grow at an annual rate that is at least equal to the discount rate.*

”*Now, if the values whose unit prices grow at a lower rate than the discount rate diminish rapidly over the years and disappear from economic calculation, those whose prices grow at the same rate will remain unchanged, and will therefore quickly dominate, and all the more so in the case of those whose prices grow even faster. In other words, in the long run, the discounting process clears everything that is of secondary importance because it can be controlled by human proficiency, to stress what is essential: i.e. whatever is intrinsically scarce and cannot be reproduced.*

”*One might object that economic calculations generally only focus on market values. But there's nothing to stop our contemporaries giving pure air, clean water or virgin land a price with a growth rate that is at least equal to the discount rate. This would in fact be the most concrete way of moving from the prophetic stage to the operational. Rather than condemning discounting, which is a necessary instrument for making consistent choices at a time when we have too great a tendency to throw out the baby with the bath water, wouldn't it be better to show that by obtusely applying discounting, at constant prices and only to market values, we are betraying what people actually experience and what they deeply aspire to in society today*.”

It must be noted that this proposal, which closely resembles the Hotelling rule (1931) regarding the exploitation of non-renewable natural resources, is in fact much more beneficial for the environment than proposals to set the discount rate at zero, because it amounts in practice to keep constant in analysis the environmental values assessed against today's economy - and only these values.

If Boiteux, like Krutilla and Fisher, rightly considers that the values of environmental goods cannot remain constant over time, his remark is different. The growth rate of environmental values is dictated neither by the rate of disappearance, nor mainly, by rising income or increasing environmental preference, but more fundamentally by the discount rate, because this rate is the corollary of investment opportunities.

If a financial flow X occurring in time t is today worth only $X/(1+i)^t$, it is fundamentally due to investment possibilities that can furnish, in time t, the goods worth X, when investing today only the sum $X/(1+i)^t$. And that is not possible for goods that technology is incapable of producing or replicating, or for which it cannot provide replacement goods. Such goods– and only such goods– are not subject to this rule.

The mandatory corollary of this proposal is naturally the adoption of a discount rate based above all on opportunity cost, i.e. the marginal rate of return on investment. If, on the contrary, a discount rate constructed mainly on the theory of consumer wellbeing is retained, this argument can no longer be used. It then becomes logical to attempt to define the growth rate for the value of environmental goods from within the same theoretical framework. But in this case, the uncertainty about this rate is added to that pertaining to the valuation of these same assets in the present.

As it happens we have already considered, in response to the first question raised, that the consumer time preference should be chosen. But this preference is not independent of the productive capacity of the economy, as shown by Irving Fisher – especially when considering a nil value for pure preference for the present and a discount rate reduced to its wealth-effect component.

The apparent differences between the American and French approaches to the progressive valuation of environmental goods, as a solution to the problems encountered in discounting these values, should not hide their common foundations: the productive capacities of the economy are the basis for interest and discounting, and it is because the economy is not able to recreate a vanished species or ecosystem that the value assigned to them should not be artificially diminished by discounting, simply because our actions might lead to their disappearance– but later. The irreplaceable nature of Nature deserves to be fully taken into account. Rabl (1996) and Markandya (1995) have recently reiterated the “Krutilla, Fisher, Boiteux” line of reasoning.

2.4. The equivalence of various arguments

Environmental costs can rise to a very significant proportion of GDP, due to their irreversible nature, i.e. the fact that the economy cannot counter them. With respect to potential catastrophic disturbances resulting from a major change in the climate in 150 years, there is nothing surprising in this. Ari Rabl's reasoning concerning the impossibility of the winners compensating the losers thus seems well-founded... But in reality, the Gross Product would have to be recalculated to include these external costs, which would modify the growth rate and, in turn, the discount rate in the direction suggested by Thomas Sterner. As was clearly perceived by Hanley and Spash (1993), “*Global warming is one of the most serious environment threats humanity currently faces. Cost benefit analysis runs into problems due to uncertainty in the estimation of benefits, attitudes towards future generations and, more fundamentally, the very size of the problem (there is a point at which marginal welfare analysis loses its theoretical basis)*”.

Another way of presenting things would be to rework and complete Weitzman's argument (1994). Here the calculation of GDP does not integrate externalities. According to Weitzman, environmental spending grows with environmental preference, and with more than proportional effects of growth on the environment. We can now add to this argument that the efficiency of environmental spending falls sharply when assets that cannot be replicated or replaced by economic means are destroyed. Thus the elasticity of environmental spending in relation to improvement of the environment, and thereby the “*environmental resistance coefficient*”, are led to grow fairly rapidly, and the discount rate to fall accordingly. Thus completed, the modelling suggested by Weitzman (1994) has an interesting feature: continuously parametrizing of the degree of irreversibility in environmental degradation, and even of the more or less reversible nature of this degradation.

3 - The uncertainty

While the probabilistic risk of a marginal investment must not influence the discount rate, insufficient knowledge of the future must incite us to be prudent, both in evaluation of growth perspectives (**3-a**) and in assessment of environmental damage (**3-b**). Paradoxically, the uncertainty on future states of the World simultaneously justifies low discount rates and prevents zero discount rate.

3.1. Uncertainty as to growth

Uncertainty as to the outcome of a marginal investment should not modify the discount rate used to perform a cost benefit analysis of this investment. Rather, the investor should compute probabilistic expected results and discount them all at the same rate. But the uncertainty on the economic growth itself is different, for its rate is a major component of the discount rate (especially if one considers that pure time preference is zero).

I have not taken a position in the debate concerning the existence of physical limits to economic growth. It can simply be recognised that uncertainty exists– the ideas developed by Weitzman (1994) and Boiteux (1976) providing some substance for Sterner's hypotheses.

This uncertainty as to long-term growth is reason enough to justify using low long-term rates– in any case lower than short-term rates, according to Christian Gollier (1997) and Martin Weitzman (1998).

For Gollier, this conclusion requires the condition, generally confirmed in his view, of a hypothesis positing the "prudence" of individuals (this prudence measures the impact of risk on the decisions made by the agent facing the risk, and is distinct from risk-aversion, defined as the impact of risk on the wellbeing of individuals). If, in addition, aversion to risk decreases with wealth, then the discount rate must be a decreasing function of the time horizon.

Weitzman (1998) does not bother with such hypotheses. It seems that his demonstration can be outlined as follows. Let us assume several states of the world in the long-term future. Each state corresponds to a growth rate, and thus to a discount rate linked to the growth rate. As the time horizon grows longer, the discount rate to be used approaches the lowest rate envisioned, the other states of the world being comparatively less important, their present value being very low due to the power of compound interest at higher rates.

If we know for sure the economic growth from time 0 to time T, then the discount rate remains unchanged. If, however, beyond time T begins a period of uncertainty, then the rate r must fall progressively and approach a value that must be the lowest value that could be conceived as a function of the states of the world imagined for the period beyond T.

Would such a proposal be "time consistent" in the sense of Solow (1999)? Yes indeed, although the value of a given capital in 2030 as computed in 2000 may take a lower value in 2010 or 2030, if at that time the future growth rate appears to be higher than the lowest previously expected. This value may change "with the passage of time", for the latter progressively reduces the uncertainty on future growth rates.

At this stage Weitzman does not exclude the possibility that this limiting long-term discount rate could be equal to zero. I am not too tempted to follow him in this direction, for the reason that uncertainty seems to me to equally warrant a minimum of discounting– including what Fisher and Krutilla (1975) called "effective" discounting, when referring to environmental assets for which valuation could rise over time at the pace of the discount rate, according to Marcel Boiteux.

3.2. The need for "effective discounting"

If we push Marcel Boiteux's reasoning to its extremes, we may come to some surprising proposals. In order to preserve in our analyses the present value of the species which we have programmed to become extinct in the very long term, we may be led to conclude (even with a declining discount rate, if it remains higher than the economic growth rate) that this species will have, for the future generation in question, a value equal to or greater than the gross world product– a hypothesis which hardly seems reasonable.

Furthermore, Marcel Boiteux's proposal suggests that there is no advantage to be had by postponing the extinction of a species – for example. This is to some extent on purpose. But this means considering this extinction as equally certain in the future as today, as a consequence of our decisions. Fisher, Krutilla and Cicchetti had already examined the concept of irreversibility of environmental damage, founding their proposal: "*Two kinds of reversal are possible, or at least conceivable. One is the restoration of an area by a program of direct investment. (...) The other kind of reversal is the natural reversion to the wild*". But they observed that "*this would seem to have little relevance for the sorts of phenomena with which we are mainly concerned: an extinct species or ecological community that cannot be resurrected, a flooded canyon that cannot be replicated, an old-growth redwood forest that cannot be restored, etc.*".

This is precisely where Marcel Boiteux's proposal can lead to logical impasses. Let us assume environmental damage of low cost, but recurring. This could be, for example, the extinction of a living species. If no time frame is set for the calculation (habitually, discounting would do this), and if the value assigned to the extinct species grows at the same pace as the discount rate (and even more so if it increases more rapidly), the present value of this species becomes infinite.

Is this a purely theoretical objection, or a realistic one? Can an environmental value approach infinity in an evolving world? It's not so clear. To continue our thinking about an extinct species, it seems likely that all species are bound to die out someday, because of the Evolution. Beyond this natural deadline, even if it is unknown, the cost of an early extinction falls to zero.

It can also be thought that, well before the time of a "natural extinction", an extinct species disappears from the realm of the possible, and it can therefore be accepted that its value will fall to zero in a few decades or centuries. The species' ecological niche is occupied by other species, possibly new ones.

One objection could be the persistence of a value of existence. Many children would be delighted to see a real living dinosaur. But if dinosaurs hadn't disappeared, the children would probably not be here to regret it.

To resolve these paradoxes we must reconsider the issue of uncertainty. With climate change, we are facing an uncertainty that leaves little room for probabilistic calculations. And this uncertainty warrants, in my view, a non-zero "effective discount" rate – a difference between the discount rate and the rate of progression over time for the values we agree to assign to natural assets.

This is not just "*the usual scholarly excuse of discounting*" which sounds "*far-fetched*" to Solow (1992): "*the small fixed probability that civilization will end during any little interval of time*". It is a more fundamental uncertainty that grows as the temporal perspective grows longer, uncertainty as to the states of the world. Perhaps this climate change will not have the deleterious effects that we have attributed to it. Perhaps science and technology, that as of today do not know how to resuscitate an extinct species or vanished ecosystem, will be able to do so tomorrow– or, more simply, will know, better than we can imagine today, how to preserve them despite climate change. "Where there is life there is hope": popular wisdom suggests that an analysis showing that there is no advantage to be had in postponing an effect which is harmful for humanity, would not be a reasonable one.

Would this idea of an "effective discounting" contradict economic theory when it establishes that the uncertainty on the outcome of a particular investment or policy should not be dealt with using a specific discount rate? I believe this is not the case, for what we are dealing here with is by no means "marginal".

It is not acceptable that discounting reduce the value of significant environmental damage to nothing, or next to nothing, solely because this damage would come several decades after our emission of pollution. Even so, economic analysis cannot grant the same weight to potential damage in 150 years, and the same damage occurring today, and no generation would claim to take on unlimited responsibility with respect to future generations. As writes Paul Ricœur (1995) "*human action is possible only under the condition of a concrete trade-off between the short-term view of responsibility limited to the foreseeable and governable effects of an action, and the long-term view of unlimited responsibility. Completely ignoring the side effects of the action would make it dishonest, but unlimited responsibility would make it impossible. It is indeed a sign of human limitations that the disparity between the desired effects and the innumerable consequences of the action is itself unmanageable, and calls upon the practical wisdom gained throughout the history of earlier trade-offs. A happy medium must be found between flight from the responsibility for consequences and the inflation of infinite responsibility*".

4 - Application to climate change

The first attempts at economic analysis of climate change led to heated debate between those who argued for low discount rates, like William Cline (1992), and those who contested his arguments, as did the World Bank economists (Birdsall and Steer, 1993) and Nordhaus (1994).

Today a set of convincing arguments has been developed which pleads in favour of rates falling ultimately to a fairly low value. But along the way the suggestion of Krutilla, Fisher and Boiteux should not be forgotten - the value of environmental assets that the economy cannot replicate or replace should grow over time - or one may underestimate climate change costs (**4-a**), and the more so if we look far in the future (**4-b**). Finally, declining discount rate and growing valuation of environmental assets are not at all independent– the second point is a part of the first, as we will see with a simple numerical illustration (**4-c**).

4.1. Underestimation of costs

It seems that the analyses available today have underestimated the real cost of climate change. Most of these studies first estimated the costs of climate change in relation to today's economy. Then they projected this value into the future at the hoped-for pace of economic growth. Lastly, by discounting, they assigned a present value to this estimate.

The analysts were well aware that this could only provide an approximation that ignored the relative variation of prices. As wrote Cline (1992), "*In reality some damages are likely to rise less than proportionately with GDP, and others more than proportionately. Agricultural effects would tend to rise less than GDP because of Engel's law (demand for food is income-*

inelastic). Such effects as electricity requirements for air conditioning might be expected to rise proportionately, or more than proportionately, with GDP, as they are likely to have unitary or above-unitary elasticity of demand with respect to per capita income. Still other effects, such as valuation on human life and the value of species loss, could be expected to rise more than proportionately with GDP. Human life valuation will reflect lifetime earnings capacity, which rises with per capita GDP; valuation of species and other ecological intangibles may be expected to be income-elastic, because economies have greater scope for allocating resources to these concerns as income rises further above subsistence levels. Overall, scaling by GDP would seem to be an appropriate approximation".

But here a balance is too hastily created between the fact that certain damages have a value which rises faster than GDP, and the fact that the value of other damages rises more slowly. Because of this equivalence all these costs estimated in the present will be globally "sent into the future" with a general economic growth rate (Cline uses 3%), then readjusted back to the present by a discount rate which is generally higher (at least during the first decades, as observed above).

To illustrate this problem, let us take a period of 50 years, a 3% expected annual growth rate in GDP, and a discount rate of 8%. A cost of 100 francs today will be estimated at 438 francs in the future, readjusted to a present value of 9.3 francs by discounting. Now let us suppose that the 100 francs are divided in two: 50 francs represent market costs of climate change, and 50 francs represent the cost of destroying absolutely rare environmental amenities.

The market values continue to be projected into the future at a rate of 3%, while the second set of values are projected into the future at 7%. Their values discounted at 8% are respectively 4.6 francs and 31.3 francs, totalling 36 francs– nearly 4 times more.

And irreversible damages do indeed represent a significant proportion of total costs calculated in today's economy: according to the survey by Arrow *et al.* (1996), 19% of the costs estimated by Cline (excluding amenities and human morbidity, and excluding certain values related to loss of species), 28% of the costs estimated by Fankhauser, close to 75% of the costs estimated by Nordhaus, 7% of the costs estimated by Titus (representing only human life, but neither human morbidity or amenities, loss of species, nor leisure activities), and lastly 73% of costs estimated by Tol (not including human morbidity).

4.2. Long-term climate change– beyond the doubling of CO_2

Another point also deserves emphasis: cost-benefit analysis of the mitigation of climate change must take into account only avoided damages as benefits. Yet it is increasingly clear– notably after the decisions made in Kyoto in December 1997– that the doubling of pre-industrial concentrations of CO_2-equivalent in the atmosphere will not be avoided (cf. Bolin, 1998). As a large majority of studies to date have focused on this (purely psychological) "threshold" of doubled CO_2, little data is available for estimating the real benefits of action aimed at holding atmospheric concentrations down to $2xCO_2$, compared to a reference scenario in which they would triple, then quadruple around 2150, reaching even higher levels in the 22nd century which might correspond to warming of 10°C or even more.

Cline (1992), Spash (1994) and Fankhauser (1995) have already remarked upon the need to analyse the effects of climate change well beyond the doubling of concentrations of carbon dioxide in the atmosphere. This comment obviously takes on considerable importance if the distance in time of the climatic catastrophe has little or no effect, as we have seen, on the present value of some of its consequences.

4.3. A numerical illustration

In this perspective it can be interesting to look at the effect of climate change on growth– and thus attempt to measure the impact in turn of the "Krutilla, Fisher, Boiteux" argument on the discount rate. For this purpose I will construct some simulations based on the hypotheses habitually associated with a doubling of CO_2 in 100 years, from pre-industrial levels: the cost of damages due to climate change (evaluated in relation to today's economy) represent 2% of gross world product. The cost of damages to intangible natural assets constitutes one half of these costs. I will apply Marcel Boiteux's suggestion, and my own suggestion of a zero pure preference for the present, and the choice of a high income-elasticity coefficient for marginal utility of income– 3, for example. In passing it should be noted that while various authors use unity for this parameter, a value synonymous with the logarithmic utility function, the literature mentions estimated rates varying between 0.8 and 2.

Let us assume an expected growth rate of 2%, and hence a discount rate of 6%.

After 100 years, GWP is multiplied by 7.2, the value of non-reproducible assets by 339, i.e. 47% of expected GWP, which, if these external costs are internalised, is only 3.8 times today's GWP (ignoring the residual term constituted by other damages). The real growth rate (here assumed to be constant over the period) is then only 1.35%.

Yet, the discount rate should then be only 4%... and the value of the intangible assets should have increased only 50 times... In fact, we are looking for the economic growth rate *g*, which will maximise the expression:

$(1+g)^T - a(1+\theta.g)^T$, with $g \leq \dot{g}$

in which T represents the time interval considered, *a* the proportion of the cost of damages to non-reproducible/replaceable environmental assets relative to gross world product, θ the absolute value of the income-elasticity of the marginal utility of income, and $\dot{g}$ the maximum growth rate for the economy.

In the present case T = 100 years, *a* = 0.01, θ = 3 and $\dot{g}$ = 2%.

The growth rate *g* is equal to 1.8%. It is therefore associated with a 5.4% discount rate, and maximal GWP in 100 years will be four times that of today, once the costs of damages inflicted by climate change are deducted, representing no less than 48% of this GWP.

Now let us suppose that T = 150 years; even without assuming more extensive climatic damage (cost of damages is still estimated at 2% of GWP, half for intangibles) we will find *g* = 1.2%, and maximum GWP only 3.8 times that of today. As T approaches infinity *g* approaches zero, if θ is greater than 1.

It must be noted here that without internalisation of the external cost in calculating GWP, the growth rate and ultimately the discount rate, we would find, for this period, a cost for damage due to climate change equal to 62 times today's GWP, and thus greater than anticipated GWP (close to 20 times today's GWP), which would hardly be credible. This would naturally arise from the problem identified by Lind and Rabl concerning the impossibility of a gap between the growth rate and the discount rate in the long term.

This problem disappears with internalisation of the external cost. But the effect of climate change on GWP growth is proportionally more significant as this event occurs later in time, which seems a bit artificial. This artifice is the price to pay for maintaining the present value of the costs of climate change– for non-reproducible environmental assets– unchanged in relation to the estimation we would make toady, if the damages were immediate. An "effective discounting" of these costs, however, would compensate for this effect. I have argued that effective discounting is legitimate, because uncertainty increases with time, implicating the choice of a discount rate slightly higher than the future valuation rate for the estimated costs of these damages.

5. Conclusions

These reflections suggest that the discount rate decreases in the long run. Among future estimated growth rates, the lowest reasonably foreseeable rate should be chosen, uncertainty as to future growth being largely nourished by environmental problems, climate change, and their effects on environmental assets that are apparently neither replaceable or reproducible. The relative value of these environmental assets must rise over time more rapidly than that of other goods, at a rate close to the discount rate.

Several conclusions and suggestions can be drawn concerning the economic analysis of climate change and the policies to be implemented to mitigate it:

- long-term costs are dominated by the costs of non-replaceable/reproducible environmental assets, including most certainly species and ecosystems, biodiversity itself (which is distinct from biological resources, following Pearce, 1999) and perhaps arable land and ground water resources;
- these values are hard to estimate, which is obviously problematic in terms of the aptitude of economic analysis to accurately establish the level of action required;
- since the value of these assets in today's economy must, ultimately, be determined by a collective decision, and seeing that economics can only hope to provide useful information for this process, economists could also propose, and the community decide, that the present value of these assets be in practice held at a constant level in economic analysis, or decrease only very slowly with the time interval that separates us from their destruction; arguably, such a proposal would not fall under the critics raised by Nordhaus (1999) against "*having technicians hide the choices in complicated and abstrusely argued second-best rules of thumb.*"
- the real cost of climate change has been underestimated hereto, and yet... mitigation of climate change, while it should be vigorously exercised, given all that has been written here, must not excessively hamper economic development; for it is this economic development that will attenuate the other categories of anticipated climate change damages (effects on agriculture, health, extreme climate events, etc.), by supplying goods and services of greater value, and helping human societies in its adaptation to climate change.

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