(The Economics of) Discounting: Unbalanced Growth, Uncertainty, and Spatial Considerations

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Abstract

The economics of climate change and the various measures that should be implemented to reduce future damages are highly tied to the use of cost-benefit analysis. Traditional approaches ignore the fact that environmental amenities do not experience the same growth rate as do most of the sectors in the economy, which leads to changing relative prices. Uncertainty should also be considered, especially when one is conducting cost-benefit analysis involving the long-run damages from climate change. This article reviews some theoretical approaches to the economics of discounting and discusses issues associated with unbalanced growth, uncertainty, and spatial discounting.

1. INTRODUCTION

When we conventionally define society's objective function of intertemporal welfare maximization, we find that discounting is numerically the mirror image of compound growth. In a growing economy, an investment is expected to give a return such that the accumulated value of the capital grows exponentially. With a real interest rate of 6% (if we abstract from inflation), the capital will increase from 100 to 106 units after one year. So we can say that a cost of 106 units in one year's time is equivalent to 100 units today. Absolute prices in an economy are always arbitrary in relation to some scalar or numeraire. To be told that the rent of a house is 100 has no meaning if we do not know the other prices—or some other prices such as a typical salary or a typical other rental price in the same economy. When we discount costs or utilities over time or space, we are in a sense making comparisons to a change in a numeraire that depends on the movement in time or space being considered.

The rest is merely arithmetic—but arithmetic that can be very powerful. Capital will double within 12 years and will multiply more than 300 times in a century. Discounting is the mirror image of this growth. Thus, a very simplistic view of the value of a cost of one billion US dollars in 500 years with 6% discounting would be 0.02 cents today. If we had used a 5% discount instead, the value of the billion dollars would have been 2 cents. This is still insignificantly small, but the reader should note that the difference between a 5% discount rate and a 6% discount rate can change the present value, in this case by a factor of 100. Discount rates can vary much more; in the literature we find values as low as 1% and as high as 10% or 12%. The discount rate is thus a parameter that is very uncertain, and the calculations are extremely sensitive even to small changes in this rate. This is an area that requires significant thought and care.

It is an understatement to say that various aspects of climate change and climate policies have featured prominently in the discourse of the past decade or two. These discussions are based largely on techniques relating to cost-benefit analysis of different measures to reduce greenhouse gases and to address environmental degradation. In this kind of analysis, the economic and environmental benefits and costs are added up, and the positive or negative result determines whether the proposed policy is profitable in economic or social terms. For example, let's assume that we consider taking some measures to reduce the use of fossil fuel. These measures are costly, but they are supposed to guarantee the sustainable use of ecosystem services, such as climate stability. If the summation of costs and benefits is positive, then the proposed measures should be undertaken because the value of ecosystem services is higher than the corresponding cost of abatement.

The concept of discounting is also closely related to the decisions that people make about their current and future consumption. Some people value their future consumption more, thus following a more conservative consumption plan at present, and others care more about the present, giving less value to future consumption. In what follows, we study the distribution of consumption across different generations (Dasgupta & Heal 1979, chapter 10).

Let $W(\{C_t\}) = W(C_0, C_1, \ldots, C_t, \ldots)$ denote the social welfare function. The objective is to find the optimal consumption paths that will maximize W. If $\{C_t\}$ is a feasible consumption profile, then the rate at which it is desirable to substitute consumption at some period t for that in the next period $t+1$ is termed the social rate of time preference between t and $t+1$, $SRTP_t$. This term ($SRTP_t$) is positive if $C_{t+1} > C_t$. One explanation follows: An extra bit of consumption at t is more valuable compared with the same extra bit of consumption at *t + 1*, as individuals at *t + 1* are assumed to consume more. Another reason why $SRTP_t$ may be positive is because people undervalue consumption in future periods compared with consumption in the present simply because $t + 1 > t$ and they care more about utility in the present. So, $SRTP_t$ is the marginal rate of indifferent substitution between consumption at *t* and consumption at *t + 1* less unity, i.e.,

$$SRTP_t \equiv -\frac{dC_{t+1}}{dC_t} - 1.$$

If we consider $W(\bar{C}_0, \bar{C}_1, \ldots, \bar{C}_{t-1}, C_t, C_{t+1}, \bar{C}_{t+2}, \ldots)$, where the bar terms imply that quantities are kept fixed, we can derive the social indifference curve, $W(\bar{C}_0, \bar{C}_1, \ldots, \bar{C}_{t-1}, C_t, C_{t+1}, \bar{C}_{t+2}, \ldots) =$ constant. The slope of this curve minus one gives $SRTP_t$.

$$\frac{\partial W(\{C_t\})}{\partial C_t} dC_t + \frac{\partial W(\{C_t\})}{\partial C_{t+1}} dC_{t+1} = 0$$

and thus

$$SRTP_t \equiv -\frac{dC_{t+1}}{dC_t} - 1 = \frac{\partial V(\{C_t\})/\partial C_t}{\partial V(\{C_t\})/\partial C_{t+1}} - 1.$$

An optimum consumption path has to be intertemporally efficient. So, efficient consumption paths can be expressed as

$$C_{t+1} = T(\bar{C}_0, \bar{C}_1, \ldots, \bar{C}_{t-1}, C_t, \bar{C}_{t+2}, \ldots).$$

Using the above relation, we can define the social rate of return on investment at *t*, r_t, as the marginal rate of transformation between consumption at dates *t* and *t + 1* minus one:

$$r_t \equiv -\frac{\partial T}{\partial C_t} - 1.$$

Now, if consumption at all other dates except for *t* and *t + 1* is kept fixed, then the best option is to choose the quantities (C_t, C_{t+1}) so that $SRTP_t = r_t$. This condition says that the marginal rate of transformation between consumption at dates *t* and *t + 1* should equal their marginal rate of indifferent substitution.

More formally, if consumption along an optimal program is positive throughout, *W* is strictly concave, and r_t is the social rate of return on investment along it, then a necessary and sufficient condition for this program to be optimal is $SRTP_t = r_t$ for all *t*. Through use of the cost-benefit-analysis terminology, the return on marginal investment (r_t) should equal the rate ($SRTP_t$) at which it is socially desirable to discount the next period's consumption.

2. DISCOUNTING AND RELATIVE PRICES

Costs and benefits must include both the current period and all future periods, and future costs and benefits must be discounted through the use of a discount or interest rate. Thus, if V_t is the future value of some cost or benefit component at time *t*, then the corresponding present value is $(1 + r)^{-t} V_t$. Even though economists use discounting widely in the context of cost-benefit analysis so as to reject or accept different projects, environmentalists have some objections to this method, mostly because they believe that we should not attribute lower values to future environmental damages to motivate more lax mitigation measures now.

There is an inevitable asymmetry in the fact that decision makers today are favored by high discount rates whereas people in the future, who will have to face the costs of damage, have no say in the choice of discount rate. Sometimes, nonlinear discount rates are also used when the expectations about the level of discount rates in the future differ significantly or for other reasons. However, another issue affects the estimations relating to future environmental damages: changes in relative prices. More specifically, even though we are aware only of current prices, the cost of future environmental damage (V_t) should be valued in real future prices. The best estimate of V_t is $V_t = V_0\ (1 + p)^t$, where p is the expected rise per year in real price of the relevant good and V_0 is the cost of environmental damage in current prices. If we consider that the good under study is an environmental resource that becomes increasingly scarce over time, the relative price is expected to rise exponentially, and this increase will affect the discounted value.

If we agree to the principles of discounting presented above, we should combine the two opposing forces, the interest rate and the relative prices, as in Equation 1:

$$V_t = V_0(1 + r)^{-t}(1 + p)^t. \tag{1}$$

Equation 1 shows that the effect of discounting could be counteracted by changes in relative price. If we believe that the object in question would appreciate rapidly in value, the effect of relative prices could be as big as that of discounting! We turn now to the issue of when and if this may be a reasonable assumption. We start with a general speculative discussion before discussing the issue more formally.

Technological change tends to increase the supply of fabricated goods, leaving the supply of environmental services unaffected. In other words, although technological advances lead to the increasing production of man-made goods given the resources used in the production process, humans are often (although not always!) unable to do the same with the natural environment due to the irreproducibility of unique phenomena of nature. For this reason, as Krutilla (1967, p. 783) explains, "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." There is no doubt that the substitutability between different classes of goods is restricted. Because the production and the consumption of produced goods grow more quickly than the production and consumption of environmental goods and services, we cannot conclude that future generations will be better off consuming more produced goods.[1]

In this article we give an overview of some aspects of the economics of discounting. We describe the Ramsey rule framework on which many of the discussions are based, and we discuss in particular the role of growth for discounting. In this area we discuss the implications of variations in the rate of growth and risk and uncertainty concerning growth. Declining growth over time may, for instance, be a motivation for declining discount rates over time. Different growth rates in different sectors may form the basis for a discussion of discount rates that vary between sectors—or the basis for the explicit inclusion of relative prices that vary over time in cost-benefit calculations. Finally, we generalize to a discussion of spatial discounting—the notion that values may change systematically with distance, as they do over time.

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[1] Although restrictive, the conventional treatment of amenity services in many studies is to assume additive separability of the underlying preferences. This assumption implies that market goods and amenities are perfect substitutes.

3. DISCOUNTING AND GROWTH

In principle, the value of future costs and benefits must depend on our expectations of the distant future. In normal projects that concern only a few years, these issues may be simple, but when we speak of problems that will unfold over centuries, we need to go back to first principles. With 6% growth we would be twice as rich in 12 years and more than 300 times richer in a century. But what does this mean? Do we today consume 300-fold-more goods and services than we did a century ago? There are obviously some exceptions such as food. We do not eat even ten times as much food as we did a century ago (although our consumption of meat has increased, which does mean that the indirect amount of acreage appropriated through, for example, pasture has increased more than we might expect). We argue that there are many fundamental changes to our consumption patterns and that we consume the same amount or less of some goods and thousands of times as much of others. Changing composition in the consumption basket is a fundamental aspect of growth.

We must carefully consider the structure of expected growth rates. We use discounting for at least two reasons (see Sterner & Coria 2011). First, an additional unit of consumption today has a higher value compared with an additional unit of consumption tomorrow, as society is considered to be impatient to enjoy that additional unit now. However, the second reason that is connected with the concept of growth is that, if future generations are expected to be richer than us, we should value an extra unit of their consumption less than an extra unit of our consumption. This leads to the use of positive discount rates. The opposite is true when consumption decreases over time. In this case, future consumption should be valued more than current consumption, which implies the use of negative discount rates. These concepts will become clearer when we present the Ramsey model below.

4. ECOSYSTEM SCARCITIES

We have little exact knowledge of the future. However, from the IPCC report (Parry et al. 2007) we do know that a considerable number of ecosystems are threatened to an extent that depends largely on the extent of radiative forcing—or, in other words, on the total quantity of greenhouse gases emitted. Among the more obvious or direct changes is the increase in temperature, which in turn will cause changes in precipitation, melting of snow, and ice and storm patterns.

We are already seeing a visible trend toward winters without snow, which will reduce the opportunity for skiing for those who enjoy winter sports. The industry strives to survive by making artificial snow on a large scale. Artificial snow is reportedly one of the biggest-cost items for some ski resorts in many places, uses much more electricity than do lifts, and incurs costs that approach a third of the income of some resorts. Even as far north as the Swedish town of Piteå on the Arctic Circle, artificial snow is made to keep the skiers happy! Another example concerns the majority of coral reefs, which are threatened with likely loss. This not only is a loss of beauty, recreation, and tourism but also has implications for storm protection, biodiversity, and fish production. Furthermore, climate change is likely to negatively affect water availability in Africa through increased drought and through the disappearance of glaciers that regulate flow in the major rivers supplying large parts of India, Bangladesh, and China, making agriculture virtually impossible in large parts of Africa and in Asia.

These effects concern the very basic biogeophysical systems that regulate conditions on Earth and that are vital for human life. These systems are not goods in any ordinary sense. Rather, they are natural factors of production or common pool resources—sometimes producing what we term ecosystem services to humanity. We cannot easily quantify the prices of these services. In many cases there are no prices (indeed, the lack of pricing for carbon dioxide disposal in the atmosphere is a root cause of the problem). However, we are facing increased scarcity of such resources, and in this sense a number of shadow "values" are or should be increasing. Consider again Equation 1: The effect of interest rates in the discounting could be counteracted or even reversed if the rate of "price" increase of the good under study were high enough. According to Hoel & Sterner (2007), the scarcity that raises the relative prices of environmental goods also has a direct effect on the discount rate itself. Using a simple Ramsey model, these authors show that the significance of these effects depends on the growth rate of the economy (or on the properties of the economy's technology) and on social preferences; see also Sterner & Persson (2008) for an application to climate economics.

5. THE RAMSEY RULE GENERALIZED TO TWO SECTORS

Formally, the derivation of discounting builds on a model of intertemporal optimization of the type $W = \int_0^T e^{-\rho t} U(C(t))dt$, where W is welfare, $C(t)$ is consumption at time t, and U is a measure of utility. The trade-offs between consumption at different points of time are given by two factors: the utility discount rate ρ and the concavity of the utility function U, which reflects the rate at which the marginal value of money falls as we get richer. In a situation with economic growth, the future is thus given lower weight the more concave U is.

If the utility function is concave, U' declines over time when consumption grows so that both terms in this expression are positive for this case. It is often assumed that the utility function has the simple form

$$U(C) = \frac{1}{1-\alpha} C^{1-\alpha} \text{ for } \alpha > 0 \text{ and } U(C) = lnC \text{ for } \alpha = 1. \tag{2}$$

This specification has the advantage that the elasticity of marginal utility with respect to consumption is constant (and equal to $-\alpha$). In this case, the appropriate discount rate r, often termed the Ramsey rate, is given by

$$r(t) = \rho + \alpha g_C(t). \tag{3}$$

In the Ramsey framework, the discount rate at time t depends on (*a*) the pure time preference ρ, which is a reflection of how much we currently value a unit of utility in the future compared with an equal unit of utility today; on (*b*) α, which accounts for social value judgments about the distribution of income among generations, i.e., the weight placed on the consumption of current (poor) generations compared with the consumption of future (rich) generations; and finally on (*c*) $g_C(t)$, the growth rate of consumption. The discount rate will be constant over time if and only if the growth rate is constant. If growth rates fall due to limits to growth or due to an economic or other crisis, then discount rates will also fall over time (see, for instance, Azar & Sterner 1996).

In the debate on the limits to growth and sustainability, the pessimists assert that eternal growth is impossible due to limited resources on a finite planet. However, the optimists (which economists these days usually are) point to technology and new sectors as sources of growth. Economists tend to reject the notion of limited economic growth. However, the arguments about a finite globe obviously carry some weight and imply that we cannot have eternal growth in sectors that use large quantities of physical material. But we could have growth in immaterial sectors. Communication and computing are examples of phenomenal economic growth that use few scarce natural resources. If future growth is concentrated only in some such sectors whereas others have constant (or even diminishing) levels of growth, then this pattern of growth implies a changing output composition and presumably rising prices in the sectors that do not grow.

If discounting, and hence growth, is essential for the valuation of future damage to environmental systems and if this growth will be highly differential between sectors, then this should be modeled explicitly. Let us build a two-sector model with E to represent some aggregate measure of the environmental quality in society, whereas C is an aggregate measure of all other goods. The utility function (Equation 2) will be replaced by $U = U(C, E)$, and we keep the constant elasticity of utility formulation from Equation 2 but insert a constant elasticity of substitution kernel to account for the interaction between C and E. This gives us the utility function (Equation 4), where σ is the elasticity of substitution:

$$U(C,E) = \frac{1}{1-\alpha}\left[(1-\gamma)C^{1-\frac{1}{\sigma}} + \gamma E^{1-\frac{1}{\sigma}}\right]^{\frac{(1-\alpha)\sigma}{\sigma-1}}. \tag{4}$$

Through the exact analog to the traditional procedure outlined above, the discount rate r is changed from Equation 3 to Equation 5; see Hoel & Sterner (2007) and Guesnerie (2004) or more general analyses in Gollier (2008) and Traeger (2011).

$$r = \rho + \left[(1-\gamma^*)\alpha + \gamma^*\frac{1}{\sigma}\right]g_C + \left[\gamma^*\left(\alpha - \frac{1}{\sigma}\right)\right]g_E. \tag{5}$$

Equation 5 is a generalization of Equation 3, with the two sectors growing at growth rates g_C and g_E. The discount rate depends (as before) on the pure rate of time preference ρ but also on a weighted average of the two growth rates. The weighting depends on the elasticity of substitution and on γ^*, which can be interpreted as the value share of environmental quality.[2]

The two discount rates coincide if either $\gamma^* = 0$ or $g_C = g_E$ (which basically means that there is no separate environmental sector) or in a number of other circumstances, for instance, if the elasticities of utility and substitution are unitary. Otherwise the discount rate can be either higher or lower. In many cases the change in relative price due to changing composition of output will be more important. The valuation of the environmental good is given by U_E/U_C, which tells us by how much current consumption must increase to just offset a deterioration in current environmental quality of one unit (i.e., to make current utility or well-being the same before and after the change in environmental quality and consumption). The relative change in this price is given by Equation 6:

$$p = \frac{\frac{d}{dt}\left(\frac{U_E}{U_C}\right)}{\left(\frac{U_E}{U_C}\right)} = \frac{1}{\sigma}(g_C - g_E). \tag{6}$$

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[2] γ^* is the share of total consumption expenditures that consumers would use on environmental quality if environmental quality were a good that could be purchased in the same manner as other consumption goods: $\gamma^* = \frac{\frac{U_E}{U_C}E}{\left(\frac{U_E}{U_C}E\right)+C} = \frac{\gamma E^{1-\frac{1}{\sigma}}}{(1-\gamma)C^{1-\frac{1}{\sigma}}+\gamma E^{1-\frac{1}{\sigma}}}$.

The rate of change in relative price will depend on the development over time of the two sectors in the economy C and E. The price change is positive, provided that consumption increases relative to environmental quality over time, and is larger the smaller is the elasticity of substitution. If the environmental quality is constant, consumption increases by 2.5% per year, and the elasticity of substitution is 0.5, this price will increase by a rate of as much as 5% per year. The relative price effect will normally counteract the effect of discounting. The combined effect of discounting and the relative price increase of environmental goods is given by $r - p$. If both r and p are positive, the sign of the combined effect is ambiguous.

The reader may note that what we here term a combined effect between relative prices and discounting could in another model be described in terms of a set of sector-specific discount rates. Mathematically, this is equivalent, but we think that the economic intuition benefits from thinking in terms of one discount rate (the rate at which we discount future costs and benefits) combined with changes in relative prices for goods in the future.

Fisher & Krutilla (1975) suggest an alternative way to take into account changes in relative values as a function of scarcity or technological change. A key issue in their analysis is that the decision to proceed with an environmental project in an area should also include the possibility of realizing the benefits that would have come from preserving the area. Evaluating a hydroelectric power project, they measure its net benefits as the difference in costs between the least-cost alternative power source and the project. In this measure, they take into account the fact that the cost of the alternative power source decreases as the old plants are progressively replaced by new technologies. As for the benefits from preserving the area and not implementing the project, they are supposed to increase over time. The explanation is simple. Rising income and education levels (together with increased scarcity) imply an increasing demand for various recreation services that can be provided only by untouched environments. Thus, a simple cost-benefit analysis that discounts benefits at a low rate—as Pigou (1932) suggested—ignores the appreciation in the value that a natural, preserved environment would have in a future time period.

Following Fisher & Krutilla (1975), we assume that b_0^d is the initial flow of net benefits from developing a hydro project in an area, b_0^p is the initial flow of net benefits from preserving the area, i is the social discount rate, δ is the rate of reduction in project benefits due to technical progress, and ζ is the rate of growth in recreation benefits due to growth in demand for this type of good. The present value of benefits from the implementation of the project at any time t is

$$b_t^d = b_0^d e^{-(i+\delta)t},$$

and the present value of benefits from preserving the area is

$$b_t^p = b_0^p e^{-(i-\zeta)t}.$$

The initial flow of benefits from the project is in effect discounted at the rate $(i + \delta)$, instead of i. The same is true for the benefits from preservations that are in effect discounted at the rate $(i - \zeta)$. The difference between the effective discount rates $(i + \delta) - (i - \zeta) = \delta + \zeta$ depends not on an arbitrarily chosen discount rate but on changes over time in relative values of project-related and preservation-related services. Thus, the present value (PV) of the project, net of environmental opportunity costs, is given by

$$PV = \int_0^{\infty} b_0^d e^{-(i+\delta)t} dt - \int_0^{\infty} b_0^p e^{-(i-\zeta)t} dt. \tag{7}$$

Porter (1982) uses the above formulation to derive threshold discount rates for projects implemented in areas providing environmental amenities. To simplify notation and to follow Porter's assumption, suppose that $b_t^d = D_t$ and $b_t^p = P_t$, and suppose also that the investment cost of the project under study is \$1. Then the present value is given by

$$PV = -1 + \int_{t=0}^{\infty} De^{-(i+\delta)t} dt - \int_{t=0}^{\infty} Pe^{-(i-\zeta)t} dt = -1 + \frac{D}{i+\delta} - \frac{P}{i-\zeta}. \tag{8}$$

It is shown that very low values of the social interest rate i do not imply that the project is profitable in financial terms. In contrast, the discount rate (i) must lie in a particular range, $i \in [i_0,\ i_1]$. For high values of interest rate, the development project is rejected because benefits are too heavily discounted to cover the initial investment cost. For very low values of discount rate, the benefits from preservation are so little discounted that they prove to be more significant than the benefits of development.

The choice of the right discount rate is crucial for the acceptance or rejection of a project. However, economic theory focuses on two different rates: the social rate of discount (or time preference, i) and the social rate of return on investment (or opportunity cost of capital, r). It is widely accepted that $r > i$, due to taxation, the public-good attribute of saving, etc. To choose one of them, it should be first decided whether the project represents changes in consumption or changes in investment. Equation 8 above is derived assuming that all the resource flows represent changes in consumption at the moment they occur. For example, the initial investment cost implies a reduction in consumption of \$1 at time $t = 0$, whereas the development benefits ($De^{-\delta t}$) or the forgone preservation benefits ($Pe^{\zeta t}$) imply changes in year t, and thus we multiply them by e^{-it}.

If there were an alternative investment plan—which means that if we rejected the one under study, we would have the opportunity to invest our money somewhere else—then the present value of this project would be

$$PV = \int_{t=0}^{\infty} re^{-it} dt + \int_{t=0}^{\infty} De^{-(i+\delta)t} dt - \int_{t=0}^{\infty} Pe^{-(i-\zeta)t} dt = -\frac{r}{i} + \frac{D}{i+\delta} - \frac{P}{i-\zeta}. \tag{9}$$

The difference between Equation 8 and Equation 9 lies in the fact that we have identified two different rates, r and i. Because $r > i$, the present value of this project is lower compared with that of the first case. The alternative options of investment make the present-value test more stringent (see Porter 1982).

The choice of the correct discount rate is elusive and depends on several case-specific assumptions. However, for issues with a very long time horizon, ethical issues, distributional issues, risk issues, and the issue of the economy's changing composition, there are solid economic foundations for modifying the simple traditional rules of thumb.

Limited substitutability between environmental and produced goods tends to increase the relative prices of environmental goods. The same idea is supported by Neumayer (1999), according to whom lower substitutability increases the weight given to the long run. He also points out the importance of substitutability compared with pure time preference in determining long-run discount rates. According to Gollier (2010), if substitutability is limited, the environmental deterioration effect dominates the economic growth effect. In this case, the discount rate is small or even negative, giving an extra incentive to preserve the environment.

Traeger (2011) decomposes the determinants of the social discount rates into a real substitutability effect and an overall growth effect. In cases in which there is perfect substitutability, Cobb-Douglas-type preferences, or equal elasticities of intertemporal and between-good substitution, social discount rates are constant in the steady state. For all other isoelastic preference specifications, social discount rates are nonconstant. As far as substitutability is concerned, Traeger shows that matters may be complex, depending on both between-good substitutability and intertemporal substitutability. If the real substitutability effect dominates the overall growth effect, the decreasing substitutability between produced consumption and environmental consumption even leads to an increase in the long-run discount rates, which implies that the weight given to the future consumption of produced goods and environmental services decreases over time.

It is not easy to find good examples of price trends of ecosystem services because ecosystem services are often nontraded public goods. We can, for a simple illustration, look at prices for land, although we must interpret them with caution because many factors influence land prices. However, they capture the general idea because the supply of land is (almost) fixed, and we typically find that the prices of land appear to rise faster than the average prices of other goods in most countries.

The idea of substitutability and people's willingness to substitute environmental goods with produced goods is highly related to the concept of technological progress, which, as noted above, positively affects the production of man-made goods. Having referred to the limited substitutability between the two kinds of goods studied here, we can now argue that the advances of technology cannot fully compensate for the depletion of natural resources. In addition, Krutilla (1967) conjectures that asymmetric technical progress due to the fixity of amenity services and the effects of real income growth on the demand for amenities would lead to increasing values of amenities relative to values of produced goods (the prices of which decline with technical progress). The increased relative prices also come as a consequence of the fact that individuals' utility relating to natural environments is increasing, whereas humans cannot enlarge the supply of this amenity. Even if the supply of the natural environment is constant—which means that strict measures are undertaken to secure its protection—technological advances that increase the supply of produced goods will affect the relative prices of environmental amenities. Thus, the relative prices of environmental goods will increase over time.

Baumol (1967) discusses how the differential productivity in different sectors influences the allocation of resources across sectors. Using a more partial analysis and assuming a linear technology, he proves that prices are determined solely by supply. In this context, he studies two types of activities: technologically progressive activities (manufacturing) and activities that permit only sporadic increases in productivity (arts or services). The model analyzed in this study is a model of unbalanced growth whereby the economy is divided into two sectors. In the first sector, labor productivity is constant, whereas in the second sector, output grows cumulatively at a constant compounded rate. The results imply that the cost per unit of output of sector one will rise unlimitedly, whereas the unit cost of sector two will remain constant. In other words, if the productivity per man-hour increases more in one of the sectors than in the other sector, then relative costs in the nonprogressive sector will increase cumulatively and without limit. Increases in the relative costs of the unproductive sector also imply increases in the relative prices of the same sector. If we think of the unproductive sector as a sector producing environmental goods, the above result could be considered an alternative explanation for the increasing relative price of environmental amenities. Interestingly, a similar point has been raised in modern macro: Focusing on the sectoral allocation of inputs at the economy level in simple static general equilibrium models, Rogerson (2008) shows that sectors with rapid growth in productivity will suffer from decreasing allocation of labor time.

Smith (1974) presents the implications of relative price change for the evaluation of a project that involves natural environments, trying to show algebraically how assumptions on the demand and supply sides influence relative prices. To do so, he allows for nonunitary income elasticity and production that lead both demand and supply influenced to affect patterns of relative prices. More specifically, he argues that in the consideration of mutually exclusive alternatives, whereby the preservation or the development of unique natural environments describes the two options, changes in the relative prices of the relating cost and benefit flows are crucial to the final result. According to the model presented in this paper (Smith 1974), economic activities are divided into two categories: (*a*) fabricated goods that are affected by technical change and (*b*) amenity services that are directly related to natural environments and that cannot be influenced by technical augmentation. The different effects that technical change has on these two kinds of goods in turn affect the production side of the market. As for the demand side, the utility function is assumed to capture the structure of demand for environmental and fabricated goods. In equilibrium, the rate at which fabricated goods and amenity services are transformed in production equals the rate at which they are substituted in consumption. Smith shows that asymmetric technological change and irreversibilities in the allocation of natural endowments to the production of fabricated goods lead to the scarcity of amenity services over time; such scarcity affects the relative prices of the two goods.

6. UNCERTAINTY AND DISCOUNT RATES

Analysts who believe that urgent action should be taken to restrict, to the extent possible, the effects of climate change know that the degree of uncertainty relating to the impact of climate change is high. This uncertainty cannot leave future interest rates unaffected (Gollier 2007, Weitzman 2007). The Ramsey approach presented above omits uncertainty. To make clear how uncertainty affects the level of discount rates, we give an example that is presented in Weitzman (2007). Interest rates under uncertainty do not aggregate arithmetically into a simple certainty-equivalent interest rate. Suppose that we have $r = 6\%$ with a probability of 1/2 and $r = 1.4$ with a probability of 1/2. One might predict that we could use the interest rate $r = 1/2 \times 6 + 1/2 \times 1.4 = 3.7$ instead. However, the correct approach is to compute not the average of the discount rates but the average of the discount factors. Thus, the expected discount factor is given by $1/2^{e^{-6}} + 1/2^{e^{-1.4}}$, which gives an effective interest rate of $r = 2\%$. The effective interest rate is very far from the arithmetic average we compute above. Thus, if we assume that the correct rate to use is r_i with a subjective probability p_i, the effective discount rate for time t is given by

$$r(t) = -\frac{ln\sum p_i e^{-r_i t}}{t}.$$

This rate decreases monotonically over time from the expected interest rate $r(0) = \sum p_i r_i$ to an asymptotic limit of $r(\infty) = min_i\{r_i\}$. Weitzman (2007) argues that the discount rates used in the Stern (2006) report, *Stern Review: The Economics of Climate Change*, may not be so wrong if we take into account uncertainty. Moreover, in cost-benefit analyses that cover long periods (for example, 100 years), discount rates must take into account the uncertainties surrounding growth and the fact that high growth rates are unlikely to persist for long time periods.

Gollier et al. (2008) argue that when uncertainty is considered, declining discount rates should be used in long-run cost-benefit analyses. The use of declining discount rates, which replaces constant discount rates, makes regulators put relatively more effort into improving social welfare in the distant future as opposed to in the short run. Other studies that explore the issue of discounting under uncertainty are Weitzman (1998, 2001), Gollier (2002, 2008), and Gollier & Weitzman (2010), which show that risk affects discounting in the following two ways. First, it decreases the level of discount rates, and second, the intensity of this precautionary effect rises with time, justifying the decreasing trend of discount rates.

We present above the Ramsey rate (see Equation 3), according to which the discount rate at time t is directly connected to the growth rate of consumption at the same time. This rate holds when there is no uncertainty about the future so that we can perfectly predict the growth rate of consumption at any time. When there is uncertainty, the growth rate of consumption should be expressed in a different way. In this case, the variation in growth—or the uncertainty—introduces a new element into optimal discounting termed the precautionary effect. To present an example, the effect of a constant certain growth rate of 5% is not the same as an uncertain varying growth rate with an expected average of 5%. In this context, following Gollier et al. (2008), we suppose that the growth rate of consumption follows a random walk. Then the growth rate per period is a random variable x with mean E_g and variance σ^2. The precautionary equivalent growth rate $\hat{g}$ can be defined as (Gollier 2008)

$$\hat{g} = E_g - 0.5\sigma^2 P_v(c_0),$$

where $P_v(c) = -cv'''(c)/v''(c)$ is the index of relative prudence of the indirect utility function. Then the short-term discount rate is given by

$$lim_{t\to 0} r(t) = \delta + \hat{g}R_v(c_0) = \delta + [E_g - 0.5\sigma^2 P_v(c_0)]R_v(c_0),$$

where δ is the known rate of time preference and $R_v(c_0) = -cv''(c_0)/v'(c_0)$ is the index of relative risk aversion of the indirect utility function.

Thus, if P_v is positive, the uncertain growth has a negative effect on the efficient discount rate, and this effect is proportional to

$$\varphi(c) = R_v(c)P_v(c) = c^2 \frac{u_{111}(c,c) + 3u_{112}(c,c) + 3u_{122}(c,c) + u_{222}(c,c)}{u_1(c,c) + u_2(c,c)}.$$

The precautionary effect is described by the first term in the numerator of the above equation (u_{111}). This term tends to reduce the discount rate, as we assume that the marginal utility of current consumption is convex in current consumption ($u_{111} \geq 0$). Thus, uncertainty about the growth rate of the economy should incentivize us to take urgent action to improve the future, specifically by decreasing the discount rate.

The challenges relating to modeling uncertain catastrophes have also been studied in different contexts. The classical cost-benefit analysis is based on expected utility theory and has been applied mostly to cope with uncertainties in the form of a known thin-tailed probability distribution function (DF). There are also other approaches connected with the fat-tailed DF. Pesaran et al. (2007) and Weitzman (2009) show that the probability distribution of the discount rate $r(t)$ under uncertainty can have a thick lower tail, which means that the likelihood for $r(t)$ to take very low values in the long run is higher than in the normal distribution. Studying the economics of catastrophic climate change, Weitzman (2009) shows that the posterior-predictive DF of high-impact, low-probability catastrophes has a tendency to be fat tailed. To explain the difference, a fat-tailed DF implies a higher probability for rare events in the extreme tails compared with the thin-tailed DF. Standard approaches to modeling the economics of climate change do not take into account the implications of large impacts with small probabilities. Weitzman (2009) argues that, although the fat-tail approach has difficult conceptual issues and less scientific conclusions compared with the more common approach of cost-benefit analysis of thin-tailed situations, the former can more adequately address issues relating to climate change.

To sum up, uncertainty implies lower discount rates in the long run, which will impede the imposition of inefficient levels of climate change mitigation. Because we cannot be completely aware of the consequences of climate change in the environment after 100 years, we also cannot take the risk of undertaking inefficient measures to mitigate climate change and thus threatening the welfare of future generations.

7. SPATIAL DISCOUNTING

When we refer to the concept of discounting, we automatically think of time discounting, which has been extensively analyzed and used in topics of various interest. However, some authors also suggest an analogy between time and space for discounting. For example, people usually care more for others who live nearby than for people living far away. An earthquake that takes place in our country and causes much disaster may create more concerns for this country's inhabitants than would an earthquake in another continent. Another example of how space directly connects to the utility or disutility we derive is the emissions generated from a factory located in our city compared with emissions from a factory that emits the same amount of pollution but that is located in another city. Thus, people may discount the welfare of others in different places in a way that is similar to how they discount the welfare of future generations across time.

The idea of spatial discounting can also be significant when environmental issues, such as the economics of climate change, are studied. In a broader context, Hannon (1987, 1994, 2005) and Perrings & Hannon (2001) develop the argument that spatial discounting is connected with the fact that people prefer to locate close to places they enjoy (parks, forests, etc.) and further from places they dislike (such as polluting sources). Perrings & Hannon (2001) explore the role of spatial discounting in the allocation of resources, which have geographically distributed nonmarket effects that diffuse with distance. They consider the rate of diffusion in effects such as the basis for spatial discounting and show that spatial discount rates above the natural rate of diffusion imply a parochial approach to the management of environmental resources. In our view, there is an analogy when it comes to preferences (we prefer proximity in space as in time). The theory of time discounting balances this preference for proximity in time against the productivity of capital in investments, which does not have any obvious counterpart in the spatial dimension. That there is no counterpart in the spatial dimension–spatial discounting approach reduces the power of the analogy, but the analogy may still be interesting to follow in other respects.

Baum & Easterling (2010) present a theory of space-time discounting and use it to analyze different aspects of adaptation to climate change. More specifically, they consider three cases of climate change adaptation: crop indemnity payments, the Commonwealth of Nations, and the climate change–migration–conflict nexus. All the cases under study indicate the significance of using space-time discounting instead of the traditional time discounting because the latter cannot capture the complexity that characterizes cost-benefit-analysis research on climate change adaptation.

In sum, there are some recent studies on spatial discounting. However, much further research is necessary before we are ready to apply the technique of spatial-temporal discounting when evaluating different projects.

8. DISCUSSION AND CONCLUSIONS

In the past few years, the economics of climate change have stimulated fierce debates over discounting. At the center of this discussion is the Stern (2006) report, which has received much criticism.[3] This report discusses the effects of global warming on the world economy, pointing out the potential impacts of climate change on water resources, food production, health, and the environment. Stern argues that urgent measures should be undertaken because the benefits of strong, early action far outweigh the costs. Stern bases both his analysis and his conclusions on highly uncertain elements, such as future damages from climate change, carbon dioxide concentrations, and future prices of carbon dioxide. However, the most controversial issue has been the much lower discount rate employed by the Stern report compared with the discount rates of previous studies on climate change.

Nordhaus, one of the most prominent economists studying the costs and benefits of climate change, criticizes the Stern review for getting the high costs relating to environmental damages through an arbitrarily low discount rate.[4] Nordhaus (2007) argues that the use of a higher discount rate will lead to more convincing results about the possible damages from climate change and about the measures we should take in the short run so as to mitigate the negative impacts. Most investigations for the negative impacts of climate change (including Stern 2006 and Nordhaus 1994) do not take into account the effects of changing relative prices, which seem to influence the calculations of the present value of costs of climate change and can be considered to be as substantial as the choice of discount rates. More specifically, we argue that the method of cost-benefit analysis for a large, long-run, and irreversible change such as climate change should be informed by the possibility that prices may change radically in the future. It is undoubtedly unrealistic to believe in constant, unwavering growth, equal for all sectors. Both logic and historic evidence show us that growth is typically concentrated in some sectors and is determined by resource availability, technical innovations, and the evolution of consumer preferences.

Because discounting is so intimately tied to growth, if sectoral growth is differential, then discounting needs to be complemented by relative price change. In this case, the effects of discounting can be counteracted, and if the increase in relative prices is fast

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[3] Among the studies criticizing the Stern review are Dasgupta (2007), Nordhaus (2007), Weitzman (2007), and Yohe (2006).

[4] In an earlier study, Nordhaus (1994) also estimated the damages from climate change, employing the well-established climate model DICE (the dynamic integrated model of climate and the economy).

enough, such effects may even be reversed. Because the irreversibility and scarcity of environmental goods lead to rising relative prices, relative prices should be included in cost-benefit analyses for climate change policies.

Substitutability between environmental and produced goods also plays an important role for relative prices and discount rates. Because man-made goods cannot cover people's needs for environmental goods and because the production of man-made goods is expected to grow faster, relative prices and discount rates should change over time. More specifically, Neumayer (1999), Guesnerie (2004), Hoel & Sterner (2007), and Gollier (2010) show that environmental deterioration and the slow growth of some sectors imply the use of smaller discount rates in those sectors (which in the case of the environment may act as an incentive to preserve it). Traeger (2011) provides the most recent and most rigorous analysis here, showing exactly under what circumstances the limited substitutability between produced and environmental consumption will lead to lower discount rates.

Technological progress also affects relative prices and discount rates. As we discuss above, in an early attempt, Krutilla (1967) argued that asymmetric technological change alters the relative values of amenity services with respect to produced goods, whose prices decline with advancing technical progress. Technological change is assumed to be asymmetric here due to the fixity of amenity services and the effects of real income growth on demand for amenities. Moreover, Baumol (1967), making the distinction between technologically progressive activities and activities with limited increases in productivity, showed that the relative production cost of the nonprogressive sector increases cumulatively and without limit. Even though he did not consider environment, his analysis on sector-specific productivities has implications for the relative values of amenities. Later, Smith (1974) tried to present algebraically how assumptions of the demand and supply sides influence relative prices. In particular, he showed that asymmetric technological change between fabricated goods and amenity services relating to natural environments and irreversibilities in the allocation of natural endowments to the production of fabricated goods directly affect the relative prices of the two goods.

Uncertainty not only about the different aspects of climate change but also about the levels of discount rate is high. In general, uncertainty is expected to decrease discount rates over time (Gollier 2007, Weitzman 2007). Other studies exploring the temporal aspect of discount rates under uncertainty are Weitzman (1998, 2001), Gollier (2002, 2008), Gollier et al. (2008), and Gollier & Weitzman (2010). All these studies justify the decreasing trend of discount rates, which in turn points out the need to take urgent action to prevent highly undesirable events and full-blown disasters.

This article also includes some spatial considerations relating to the concept of discounting. In particular, because there is some evidence that people discount the welfare of others, particularly the welfare of those living in distant places, the spatial aspect of discounting should not be ignored. In the case of the economics of climate change, in which the negative effects will vary significantly in different spatial points, space-time discounting may better describe and indicate the appropriate abatement policy. This argument becomes even stronger if we consider one of the main conclusions of the Stern report: The impacts of climate change will not be evenly distributed—poor countries and people will suffer earlier and more. This conclusion may also underline the need to be more concerned about developing countries, which are expected to face more severe effects. However, much work still needs to be done as to the correct approach to spatial discounting.

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