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A Dual Probabilistic Discounting Approach to Assess Economic and Environmental Impacts

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Abstract

The growing environmental concerns require the characterization of decision support methods that can guide analysts towards more sustainable investment choices. Therefore, in the *ex-ante* economic evaluations of investments with environmental repercussions, it is of rising interest to give the "right" value to the non-monetary effects in the long term. In this regard, conventional discounting procedures—based on constant rates—are inadequate to evaluate intergenerational environmental effects. With this research we propose an innovative model for estimating discount rates to be used in the Cost–Benefit Analysis (CBA) of projects with long-term environmental effects. The model is based on a two-goods extension of the Ramsey formula, according to which the rate at which environmental impacts are discounted is different from the rate at which monetary benefits are discounted. Compared to the Ramsey model, we propose time-declining functions of the two discount rates to assess the long-run effects of investment projects. To characterize the model, we consider the macroeconomic risk, or we assume that the variable "GDP growth rate" is a stochastic variable. Furthermore, since we propose discount rates to evaluate public projects in line with sustainable development goals, we express environmental quality as a function of the Environmental Performance Index (EPI). Based on the proposed model, we estimate for the first time declining consumption discount rates and declining environmental discount rates for Italy based on empirical data. The estimates of the two discount rates for Italy shows that the environmental discount rate is lower than the consumption one: in fact, the first one starts from a value of 3.0% and arrives at 0.4% after 300 years; while the second one starts from 0.7% and reaches 0.3% at the end of the considered time horizon. The result highlights the importance of estimating country-specific dual and declining discount rates. These discount rates allow appropriate weights to be given to all investment impacts, and therefore also to environmental impacts, compared to conventional discounting.

Keywords Environmental projects · Dual discounting · Environmental performance index · Economic evaluation of the projects

JEL Classification H43 · D61

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1 Introduction

The rapid economic and demographic growth in recent decades, the increase in living standards, the consequent unplanned urbanization process with the huge increasing production of waste related to it, are among the key causes of the overuse of natural resources and the disproportionate anthropogenic pressure on the environment (Mehzabeen et al. 2018). On the one side, this has driven towards new approaches to sustainable development, such as the food-energy-water nexus, the green/blue and circular economy, or the green/smart cities to better the quality of life (Chang et al. 2016; Ansari et al. 2018). On the other hand, there is the need for new decision support methodologies to select environmentally, economically, and socially sustainable design alternatives. Therefore, in *ex-ante* economic evaluations of investments with environmental effects, it is of growing interest to consider all possible long-term implications that may be generated by the investment projects (Nesticò and Maselli 2018). These environmental components must then be transformed into monetary terms and finally discounted to give them the "right" weight in the Cost–Benefit Analysis (CBA). This means choosing "correctly" the Social Discount Rate (SDR) that represents the rate at which the community is willing to exchange present for future consumption (Evans and Kula 2009). The question of the choice of SDR becomes particularly critical when considering projects whose benefits are only evident in the very long term. This is because conventional discounting procedures use constant discount rates over time, i.e. the discounting of financial items is generally carried out through an exponential discount function. However, this leads to an excessive decrease of the discounted value of the costs and benefits arising from the project for future generations.

In this regard, consider the investments for sustainable development of the urban environment: urban forestation interventions, whose effects can be found at least 20 years after planting; projects for green cities/smart, whose investment costs are high while the greatest benefits are manifested in the long term; again, interventions on water resources, which also generate multiple effects over a long period of time (Nesticò and Maselli 2019; 2020a). These are investments whose benefits are often passed on to generations other than those who bear the costs and for which the use of constant rates in the economic viability analyses would lead to underestimating environmental effects progressively more far away (Gollier 2010; Moxnes 2014).

To overcome this problem, some scholars propose to use time-declining discount rates (or Declining Discount Rates, DDRs) instead of constant. In this way, the policy maker will be more committed to improving social welfare in the distant future than in a shorter time (Weitzman 1998, 2001; Groom et al. 2007; Cropper et al. 2014; Freeman et al. 2015). Kula and Evans (2011), on the other hand, argue that discounting has a critical impact on sustainability, so that the use of DDRs could also give more weight to the present and the near future. Thus, according to this viewpoint, several scholars believe that environmental consequences should be discounted in a different way from economic ones (Weikard and Zhu 2005; Viscusi et al. 2008; Gollier 2008, 2010, 2011; Almansa and Martínez-Paz 2011). This means that especially in a moment of high decline for the global environment, such as the one we are experiencing, a dual discount rate for projects with a considerable environmental impact should be used in the cost–benefit analysis:

- a discount rate for strictly financial cash flows;
- another lower value rate for the assessment of environmental externalities (Kula and Evans 2011).

With this research we want to show the need to use specific discount rates for human-made goods and environmental goods in Cost–Benefit Analyses of public projects aimed at achieving Sustainable Development Goals (SDGs). Since these are investments with long-term effects, we estimate—based on a two-goods extension of the Ramsey formula—time-declining consumption discount rates higher than the environmental discount rates. In the literature, there are still no examples of declining dual discounting, but the two approaches are always treated separately. Here, however, we show that it is possible to define term structures of the two discount rates, environmental and consumption, that are decreasing in time. Specifically, we assume that the "consumption growth rate" is a stochastic variable, thus obtaining a probabilistic function for both consumption and environmental discount rates. The idea is to assume that the growth rate of consumption is a risky parameter. This is a legitimate assumption since, as the relevant time series show, the trend of this variable is not stable but is subject to shocks that are difficult to predict. Therefore, we find it more consistent to express this parameter in probabilistic rather than deterministic terms.

Therefore, starting from the probability distribution of the variable "consumption growth rate", we derive the probability distributions of the two discount rates (consumption and environmental) by implementing Monte Carlo analysis. According to the logic of the Expected Net Present Value (ENPV), estimating the ENPV with an uncertain but constant discount rate is equivalent to calculating the Net Present Value with a certain but decreasing certainty-equivalent rate until reaching the minimum possible value at time equal to infinity (Newell and Pizer 2003). Thus, according to this approach, we move from the "uncertain" and constant discount rate to a certain but decreasing discount rate over time by estimating the "certainty-equivalent" consumption and environmental discount factors for each future instant t. We therefore want to show that, starting from the two-goods extension of the Ramsey formula, we can define the term structures of the two discount rates by accounting for the uncertainty inherent in the growth rate of consumption and hence of the economy.

In addition, as we propose discount rates to evaluate public projects that are in line with UN's targets, we express environmental quality as a function of an Environmental Performance Index (EPI). Proposed by the Center for Environmental Law & Policy (Yale University) and the Center for International Earth Science Information Network (Columbia University), EPI is a composite index ranking 180 countries based on 24 key performance indicators. These 24 indicators are included in ten categories, covering issues related to ecosystem vitality and environmental health. Therefore, this index makes it possible to determine how close countries are to achieving the United Nations' 2015 Sustainable Development Goals (Wendling et al. 2018).

Based on the proposed framework, we estimate for the first time declining consumption discount rates and declining environmental discount rates for Italy based on empirical data.

The paper consists of five sections. The following Sect. 2 provides the literature review of approaches to discounting, both traditional and those that distinguish consumption and environmental discounting. In Sect. 3, we propose the theoretical framework for the dual and declining discounting model. In Sect. 4, we estimate the environmental and consumption DDRs for Italy. In the last section, we draw conclusions.

2 Literature Review

The literature highlights the need to use alternative procedures to those conventionally used to assess the Social Discount Rate (SDR) to be used in the Environmental Cost–Benefit Analysis. To analyse these approaches, the theoretical assumptions underlying conventional discounting procedures, i.e. conducted with constant discount rates (Sect. 2.1), are explained; then an overview is provided on approaches such as hyperbolic discounting with Declining Discount Rates (Sect. 2.2) and dual discounting, based on the use of two separate discount rates, the consumption and environmental one (Sect. 2.3). Finally, Sect. 2.4 collects a set of empirical estimates of the discounting parameters.

2.1 The Rationale of Discounting

Discounting is a necessary operation to make cash flows financially comparable over time (Müller 2013). Consequently, discounting significantly influences the result of the cost–benefit analysis (CBA). Price (1988) defines SDR as that "discount rate used by society to give relative weight to social consumption or income accruing at different points in time". The SDR can reflect on the one hand, the meaning of Social Opportunity Cost of Capital (SOC) if it expresses the investor's point of view, for whom a dollar spent today, has an opportunity cost of loss of earnings in the future (Pearce and Ulph 1999; Nesticò and Maselli 2020b). On the other hand, SDR can have the meaning of marginal Social Rate of Time Preference (SRTP) if it represents the perspective of the consumer. In this perspective, the SRTP is the rate at which society is willing to delay a marginal unit of current consumption to receive more future consumption. There are three main arguments why future assets have lower value than present ones. In the first place, because assets are more easily accessible, the value of their marginal utility decreases with time. Second, individuals tend to consume sooner rather than later because they are impatient. Finally, productivity increases over time, so future goods are easier to produce, and it is legitimate to assume that consumption will also increase in time (Weikard and Zhu 2005).

According to the SRTP approach, the social welfare depends only on the utility of consumption $U(c)$. The hypothesis on which the SRTP approach is based is that the society's well-being is an intertemporal aggregate of the utility of consumption only. Therefore, consider the function of inter-temporal social welfare W in terms of the amount of consumption utilities for each moment in time:

$$W = \int_{t=0}^{\infty} U(c_t) \mathrm{e}^{-\rho t} \mathrm{d}t \tag{1}$$

In (1), $U(c_t)$ is a time-invariant utility function and represents the utility that society derives from public and private per-capita consumption during period t; $\mathrm{e}^{-\rho t}$ is the discount factor (or weight) that applies to the incremental utility from more consumption in period t; e is the exponential function; and ρ is the utility discount rate, also called pure time preference rate. According to Weikard and Zhu (2005): «the weight of utility from consumption declines over time with rate ρ. In other words, the utility discount rate is the rate at which the present value of a small increment of utility falls as its date of receipt is delayed».

Even if we assume a utility discount rate of zero, the value of a unit of consumption can change over time. The rate r of this change is called the consumption discount rate or Social Discount Rate (SDR), since it is used to evaluate the effects—financial and extra-financial—that public projects generate for the community.

The utility discount rate and the consumption discount rate are related through the intertemporal welfare function (1). In particular, considering that: (i) r is the rate at which the value of a small increase in consumption decreases with time; (ii) η is the value of the elasticity of marginal utility with respect to consumption; (iii) $U(c)$ is twice differentiable and time invariant; then we can obtain the well-known Ramsey's formula (1928)[1]:

$$r = \rho + \eta \cdot g \tag{2}$$

where: ρ is rate of pure time preference; η is the consumption elasticity of marginal utility that describes the change of marginal utility when consumption changes; g is the growth rate of consumption that details how quickly consumption increases.

Ramsey's formula makes clear the relation between the discount rate of utility ρ and the discount rate of consumption r and shows that if $\rho \geq 0$, $\eta > 0$, $g > 0$, then the discount rate of consumption r is positive and future assets are lower in value than current assets.

2.2 Declining Discount Rates (DDRs)

Scholars such as Yang (2003), Price (2010), Echazu et al. (2012) and Davidson (2014) are sceptical about the use of conventional discounting, which is based on the use of constant discount rates, in CBA. According to OECD (2018) high costs and benefits maturing in the future may become meaningless in present value, as the shadow price associated with them becomes evanescent. The effect of contraction on cash flows has led to problems of an ethical nature and of intergenerational equity, for which we often speak of the "tyranny of discounting". This is particularly true when it is necessary to evaluate environmental projects and policies as long-term damage and/or benefits may not be considered in economic evaluations (Gollier 2010). It has been said that, according to some scholars, a possibility to give more weight to distant Cash Flows (CFs) over time is to use Declining Discount Rates (DDRs) instead of constant discount rates (Henderson and Bateman 1995; Almansa and Martínez-Paz 2011). Declining discounting is based on the use of a hyperbolic rather than exponential function for the discount factor. Consequently, project costs and benefits are discounted less heavily by using decreasing discount rates instead of constant ones. In this way, more weight is given to consumption and environmental impacts that are distant in time (Henderson and Langford 1998; Frederick et al. 2002). The "political" justification for the use of time-varying discount rates is the following «in one swoop this would help to resolve the long-standing tension between those who believe the distant future matters and those who want to continue discounting the future in the traditional way» (Pearce et al. 2003). Weitzman (2001) clarifies that the discounting of climate change impacts is incomplete if conducted without the declining logic. In the United Kingdom, Norway, Denmark and France, the use of time-declining discount rates is now common practice. The Green Book (HM Treasury 2003) suggested a declining discount rate which starts at 3.5% and reaches 1.0% after 300 years. Kula (2008) believes that this decrease is even too small to significantly influence the outputs of the evaluation.

The DDR finds the first theoretical assumptions in the works of Kula (1988) and Bellinger (1991) which provides a theoretical justification for hyperbolic discounting. Moreover, the most important contributions to the theory are in the definition of the two

[1] For an in-depth analysis of mathematical passages see Weikard and Zhu (2005).

main theoretical approaches for the estimation of the DDR: (i) the Consumption-Based Approach; and (ii) the Expected Net Present Value Approach.

The first approach is based on Ramsey's formula (2), introduced in the previous paragraph. In this case, however, the hypothesis that the growth rate *g* is uncertain allows estimating a function of the discount rate decreasing over time (Gollier 2010, 2011). According to the second approach, however, the discount rate *r* is treated as an uncertain parameter. This hypothesis leads to the definition of a decreasing SDR structure (Newell and Pizer 2003; Cropper et al. 2014; Freeman et al. 2015). When the time horizon is long, it is important to consider the riskiness of future benefits. Traeger (2013) highlights that the uncertainty of future economic development affects the term structure of discount rates and thus the intertemporal weights to be employed in cost–benefit analysis. He shows that increasing and decreasing discount rates have different meanings but can co-exist in evaluations. Luo et al. (2020) investigate the impact of aggregate risk and diversifiable idiosyncratic risk on the discount rate, showing that non-diversifiable idiosyncratic risk reduces the discount rate and increases the present value of uncertain future project benefits.

2.3 Dual Discounting

Recent contributions to the debate on environmental discounting, encouraged by the global effort to fight climate change, concern the application of two distinct discount rates, which are useful for assessing consumption and environmental quality separately (Plambeck et al. 1997; Yang 2003; Gollier 2010; Almansa and Martínez-Paz 2011; Defrancesco et al. 2014).

The reasons that can justify the choice of dual-rate discounting have been analysed by several authors.

Price (1993) considers that it is not correct to apply a single discount rate to evaluate different types of future goods, since the different utility trends derived from the different goods (consumption and environmental) should influence the project evaluation. Tol (2003) argues that the reason for the dual discount rate is that public goods or environmental quality become more important than conventional consumption. Gollier (2010) points out that the economic justification for discounting is based on a wealth effect: if one believes that future generations will be richer than current ones, then an incremental unit of consumption is more valuable today than tomorrow. However, multiple impacts of climate change, such as loss of biodiversity, degradation of environmental assets and ecosystem services, and rising temperatures, affect environmental quality rather than consumption. Therefore, if we believe that the environment is deteriorating over time and assume that marginal utility is decreasing in environmental quality, then improving the quality of the environment will be more valuable for future generations than for today's. This argument justifies the use of dual discounting and advocates a lower discount rate for changes in the environment than for changes in consumption.

Similarly, Baumgärtner et al. (2015) argue that most ecosystem services are globally in decline, while the production of consumer goods, as measured by Gross Domestic Product (GDP), is still growing. This opposite development between environment and consumption would justify the use of specific discount rates for manufactured consumption goods and for ecosystem services.

We agree with these arguments and believe that discounting environmental impacts separately from economic ones becomes a way to guide the decision-maker towards more sustainable choices. Many studies have been carried out in this direction. Some authors analyze the dual discount issue from a theoretical perspective, coming to the overall finding that environmental goods would be discounted at a lower discount rate than human-made goods (Weikard and Zhu 2005; Gollier 2010; Echazu et al. 2012; Guéant et al. 2012). Other authors, however, conduct empirical studies on environmental discounting. Richards and Green (2015) estimate a hyperbolic and smaller discount rate for environmental assets than the financial one. Echazu et al. (2012) suggest that over medium to long term horizons the environmental discount rate should be lower than the time preference rate, supporting recent proposals for immediate action to mitigate climate change. Guéant et al. (2012) define a model for estimating the discount rate to be used in projects aimed at preserving the environment. The model has two different goods: one is the usual consumer good whose production can increase exponentially, and the other is an environmental good whose quality remains limited. Therefore, the authors define an environmental discount rate and analyse its connections with the usual interest rate and the optimised growth rate.

Baumgärtner et al. (2015) find lower discount rates for ecosystem services than for manufactured goods. They find that in all five countries studied—Brazil, Germany, India, Namibia, United Kingdom—aggregate ecosystem services should be discounted at a significantly lower rate than that for manufactured goods, with the difference between the two discount rates ranging from $0.5 \pm 0.3\%$ points (Brazil) to $2.1 \pm 0.9\%$ points (India). The difference is larger in less developed countries (India, Namibia) and smaller in more developed countries (Germany). Considering instead the global average over all ecosystem services studied, they find that ecosystem services should be discounted at a rate that is $0.9 \pm 0.3\%$. In summary, this application demonstrates, firstly, that public cost–benefit analyses of projects with consumption and environmental impacts should indeed differ. Secondly, it shows that it is necessary to use country-specific discount rates. Indeed, developing countries face a double challenge: while (i) ecosystem services essential for human well-being are in decline, (ii) applying a lower discount rate on ecosystem services implies higher opportunity costs of economic or social development projects. Drupp (2018) comes to similar conclusions by implementing a model based on constant elasticity of substitution (CES) utility specification and global metadata on willingness to pay for several ESs. Again, Vazquez-Lavín et al. (2019) stress the importance of estimating a declining discount rate for ecosystem services. Zhu et al. (2019) also argue that the discount rate for cost–benefit analysis must consider the future scarcity of ecosystem services in consumption and production. This paper analyses three cases: (i) if ecosystem services can be easily substituted, the discount rate converges towards the usual value in the long run; (ii) if ecosystem services can be easily substituted in production but not in consumption, the effect of relative price is important; (iii) if ecosystem services cannot be easily substituted in production, the discount rate decreases towards a low value, and the effect of relative price is less important. In other words, it is shown that the appropriate discounting rule crucially depends on the role of ecosystem services in production. While the need to use discount rates for ecosystem services that decline towards lower values in some cases is highlighted, the model is not yet calibrated to real data.

The Netherlands has proposed different discount rates for several sectors. If the default discount rate is 3%, a 4.5% discount rate is applied to public infrastructure. Again, nature is discounted at 2%, while nature replaceable at 3%. The same happens to discount carbon emissions and health (O’ Mahony 2021). The latest update of the UK Green Book (Treasury HM 2018) applies a lower than standard discount rate of 1.5% to human health. These examples demonstrate how much the need to propose dual discounting is spreading in practice.

Kyllonen and Basso (2017) highlight that there is a growing willingness among economists to use resource-specific discount rates. Central to this debate was the Stern Review on the Economics of Climate Change (Stern 2007), which discussed the need to apply specific discount rates for assessing climate change impacts and mitigation costs. Stern did not use a single discount rate but applied a stochastic approach. However, the average discount rate estimated by Stern for climate change damages is about 1.4%.

In order to define a dual discounting approach, it is necessary that the utility function—already defined in paragraph 2.1– depends both on the consumption of c_t and on the environmental quality q_t, namely $U_t = U(c_t, q_t)$. The function of inter-temporal social welfare W becomes a function of both c_t consumption and environmental quality q_t:

$$W = \int_{t=0}^{\infty} U(c_t, q_t) \cdot \mathrm{e}^{-\rho t} \mathrm{d}t \tag{3}$$

To obtain a function of the consumption discount rate different from the one used to estimate the environmental discount rate, Gollier (2010) extends Ramsey's rule by considering the degree of substitutability between the two goods (consumption and environmental quality) and the uncertainty surrounding consumption and environmental growth. Specifically, in one of the specifications considered, he shows that under certainty and Cobb–Douglas preferences the difference between the consumption and environmental discount rates is equal to the difference between the consumption and environmental growth rates.

In addition, he supposes that:

(i) $U(c_t, q_t) = kc_t^{1-\eta_1} q_t^{1-\eta_2}$;
(ii) $q_t = c_t^{\delta}$;
(iii) c_t follows a geometric Brownian motion.

This results in the following two equations:

$$r_c = \rho + \left[\eta_1 + \delta \cdot (\eta_2 - 1)\right] \cdot \left[g_1 - 0.5 \cdot (1 + \eta_1 + \delta \cdot \left(\eta_2 - 1\right) \cdot \sigma_1\right] \tag{4}$$

$$r_q = \rho + \left[\left(\delta \cdot \eta_2 + \eta_1 - 1\right)\right] \cdot \left[g_1 - 0.5 \cdot \left(\delta \cdot \eta_2 + \eta_1\right) \cdot \sigma_1\right] \tag{5}$$

where:

ρ is the rate of pure time preference;
η_1 represents the aversion to risk on consumption;
η_2 expresses the aversion to environmental risk;
g_1 the consumption growth rate;
σ_1 is the variance of g_1;
δ is the elasticity of environmental quality with respect to consumption.

Gollier (2010), using data on the link between biodiversity and economic development, estimates that the rate for discounting changes in biodiversity is 1.5%, while the discount rate to be applied to changes in consumption is 3.2%.

2.4 Overview of Empirical Estimations of Discounting Parameters

Many empirical estimates of discount parameters have been conducted in the literature.

The rate of time preference ρ is also called "intergenerational discrimination rate". It expresses the value that people attribute to the well-being of the present generation compared to that of the following generation (Heal 2009). Some authors consider that ρ is supposed to have a very small but not nil value. This is for two reasons. First, to consider the possibility of natural catastrophes (Stern 2007); second, because people tend to promote the health of their families over the future well-being of strangers (Nordhaus 2008). According to Florio and Sirtori (2013), the rate of pure time preference, in turn, can be broken down into two terms, one related to the impatience and short-sightedness of individuals and the other related to the risk of death or extinction of the human race. Impatience refers to the observation that individuals favour present consumption over future consumption and is reflected in a positive value of ρ. According to Zhuang et al. (2007), the difficulty of empirically estimating this first component of pure time preference may be the reason why many studies have ignored it. The second component of the pure time preference rate, namely the risk of death, is generally approximated by the ratio of total deaths to total population (Pearce and Ulph 1999; Evans 2006). Pearce and Ulph (1999) argue that the first rate is in the 0%–0.5% range; based on death rate statistics, they argue that a figure close to 1% is consistent for the second term (the death rate). Adding these two elements together, the authors suggest that a figure close to 1.5% for the utility rate discount rate is consistent. In contrast, authors such as Evans and Sezer (2005) and Kula (2004) have opted for a measure of ρ based only on mortality and obtained results close to 1%. Different is the position of Stern (2007), who instead believes that the "pure time discount rate" is of great importance for a long-term challenge such as climate change. It is an important parameter because it allows to explain the exogenous possibility of extinction deriving from some possible external shock to the problems and choices in question. From this point of view, it should be small. On the other hand, those who would attach little weight to the future would likewise show little concern for the problem of climate change. The estimation of this parameter requires a consideration of the ethical issues related to the comparison of the incidence of costs and benefits between generations, some of which are very distant in time. According to Stern (2007): «This means that we evaluate the impacts on our children and grandchildren, which are a direct consequence of our own actions, as much as we evaluate the impacts on ourselves». Defining what the most appropriate value for ρ is not easy. However, since the possibility that the human race could become extinct appears to be low, the Author believes it is consistent to assume a low pure time preference rate of 0.1%, which corresponds to a 90% probability that humanity will survive for a while period of 100 years.

Empirical estimates of the elasticity of marginal utility of consumption also vary considerably across studies. This is because the estimation varies depending on the approach used. The most widely used approaches are the following: (i) direct survey methods; (ii) indirect behavioural evidence; (iii) revealed social values or the equal-sacrifice income tax approach.

Methods referring to (i) focus on measuring risk aversion and inequality based on responses to specially structured questionnaires. It is evident that estimates of this parameter based on survey evidence regarding both risk aversion and inequality aversion are sensitive to the nature of the questions asked and the types of respondents addressed. Moreover, surveys are costly in terms of both time and money, and it is necessary to cover representative cross-sections of the general public in order to obtain appropriate values for this parameter (Evans 2005).

Approach (ii) is based on consumption behaviour observed by empirically estimated consumer demand patterns, and it can be based on: (a) models of lifetime consumption behaviour; and (b) consumer demand models for 'preference-independent goods' (Evans 2005). According to the first model (a), the parameter is interpreted as the reciprocal of the intertemporal elasticity of substitution in consumption. In this case, the critical issues are related to the particular interest rate to use, the need to consider the large difference between retail loan and saving rates, especially in the absence of fixed mark-ups by financial institutions. Model (b) formulated by Frisch (1959) is based on the assumed existence of additive preferences (elsewhere this property is referred to as 'strong separability' or 'wants independence'). Additivity implies that the additional utility obtained from consuming additional units of the additively separable good is independent of the quantity consumed of any other good. therefore, this model is said to be used for 'wants independent goods' or 'preference-independent goods' (Groom and Maddison 2013, 2019). It is shown to be a good approximation that, for a preference-independent good with a relatively small share in the consumer budget, the value of η_1 is given by the ratio of the income elasticity of demand to the compensated own-price elasticity. As Evans (2005) points out: «Results for η_1 based on this model have been generally disregarded in the literature, mainly because of the strong additive separability condition (preference independence) that is required for the approach to be valid». This condition is unreasonably stringent, as in the absence of additive separability, and is meaningless: for each monotonic transformation of the underlying preference function, a different value of η_1 would emerge (Evans 2005).

Approach (iii), also called 'the equal absolute sacrifice approach' entails inference from government behaviour revealed through spending and tax policies. Cowell and Gardiner (1999) argue that decisions on taxation have to be defended before an electorate and the values implicit in them ought, therefore, to be applicable in other areas where distributional considerations are important such as discounting or the determination of welfare weights. Groom and Maddison (2013, 2019) point out that tests of the equality of sacrifice assumption are themselves impossible since they are necessarily based on a particular utility function. Evans (2005) highlights that simplicity of implementation is the virtue of this method.

Empirical estimates based on these approaches indicate that the values of η_1 are generally between 1 and 2. Just to mention a few, Evans and Sezer (2005) apply the absolute sacrifice parity approach to EU countries and find that values are between 1.3 and 1.6. Evans (2005) estimates the value of η_1 for evaluating social projects in 20 OECD countries using the personal income tax rate structure approach. He suggests that, on average, for developed countries η_1 is close to 1.4. Gollier (2007) estimates values around 4 based on experimental evidence on risk aversion. Based on introspection on inequality aversion, Dasgupta (2008) prefers a value of 2. Florio and Sirtori (2013) propose an average η_1 for the EU countries of 1.50 for the year 2011, with a minimum η_1 value of 1.09 for Poland and a maximum value for η_1 of 1.86 for Portugal. Nesticò and Maselli (2020a, b) estimate a value for η_1 of around 1.3 for both Italy and the US, using approach (iii). Groom and Maddison (2019) provide empirical estimates of η_1 for the United Kingdom using four revealed preference techniques: the equal-sacrifice income tax approach, the Euler-equation approach, the Frisch additive-preferences approach and risk aversion in insurance markets. By implementing the different approaches, they obtain an eta value ranging from 1.320 to 2.187. In addition, they conduct a meta-analysis which indicates parameter homogeneity between the approaches and a central estimate of 1.5 for η_1. They believe that the implemented approaches are also valid for the evaluation of long-term projects. In fact, term structure of the SDR is then estimated. The result is a short-run SDR of 4.5% declining to 4.2% in the very long-run.

g_1 is generally approximated to the average annual growth rate of per capita consumption. Averaging time data 1970–2011, Evans and Sezer (2005), estimate $g_1 = 2.3\%$ for Spain; $g_1 = 2.5\%$ for Italy and Greece, $g_1 = 3\%$ for Ireland. Percoco (2008) and Florio and Sirtori suggest using average growth rate of GDP per capita as a proxy variable for the growth rate of consumption. Following this approach, Percoco (2008) estimates a g_1 value of 2.1 per cent for Italy (1980–2004 period). Florio and Sirtori (2013) estimate the value of this parameter for each EU country: the average value for EU Countries is about 1.4%. Nesticò and Maselli (2020a, b) derive for Italy $g_1 = 1.3\%$ and for the US $g_1 = 2.7\%$.

Rarer in the literature are calibrations for environmental parameters which are an extension of the Ramsey formula for dual discounting approaches. The degree of environmental risk aversion η_2 difficult to calibrate. Gollier (2010, 2011) assumes that this parameter is a function of consumption expenditure to be assigned to environmental quality (the formula is given in Sect. 3, step 2). According to Hoel and Sterner (2007) and Sterner and Persson (2008) it is consistent to assume that consumption expenditure to be assigned to environmental quality is between 10 and 50%. In agreement with this assumption, Gollier (2010) assumes a value for this parameter of 30%, and he estimates a value of $\eta_2 = 1.4$. Finally, to estimate δ, Gollier (2010) uses the indicator that measures for 146 countries in 2005 the percentage of total area (including inland waters) with a very high anthropogenic impact. The indicator is contained in the Environmental Sustainability Index (2005). Estimating a value of 0.10 in absolute terms for δ, gives an consumption discount rate of 3.2% and an environmental discount rate of 1.5%.

3 Method. A Novel Model for Dual Discounting

The literature review showed that dual and declining approaches are becoming increasingly popular but have rarely been used together. Since with this study we focus on discount rates to be applied for projects with long-term environmental effects, we propose to calibrate an estimation model based on the joint use of dual and declining discounting for further applications. Our study is based on a two-goods extension of the Ramsey growth model, which is represented by formulae (4) and (5) in Sect. 2.3.

As the model is used to estimate a discount rate that can weigh long-run effects, we cannot neglect the riskiness related to the macroeconomic variable g_1. This variable, which is expressed by a country's GDP growth rate, cannot be modelled as a deterministic variable. An analysis of the historical series of GDP shows that this variable is subject to multiple shocks linked to economic cycles. For this reason, in our model we consider macroeconomic risk by representing g_t as a stochastic variable. This means that we first identify the probability function that best fits the historical data. Then, implementing Monte Carlo analysis, we derive the probability distributions of r_c and r_q. According to the logic of Expected Net Present Value (ENPV), estimating ENPV with an uncertain but constant discount rate and calculating Net Present Value with a certain but decreasing rate is equivalent to certainty. Therefore, we move from a probable and constant discount rate to a discount rate that is certain but decreases over time with an equivalent certainty, as described in Sect. 3.2. Following this logic, we obtain discount rates r_{ct} and r_{qt} that decline over time as the macroeconomic risk is considered. This model aims to show that a decreasing discount

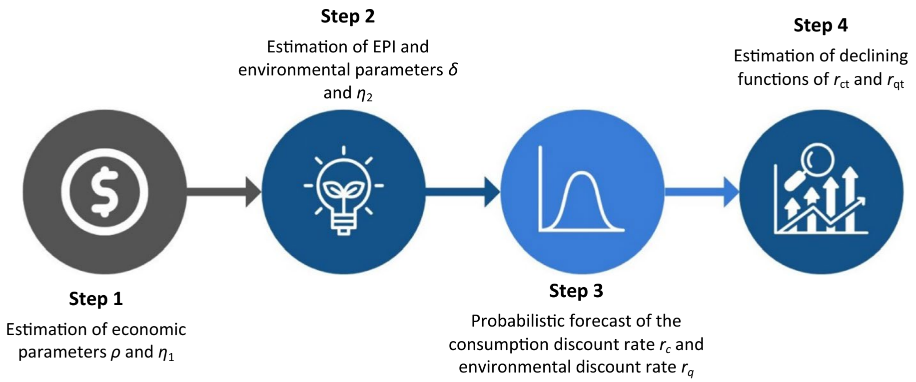

Fig. 1 Model phases

rate is related to the inherent uncertainty in the growth rate of consumption and thus of the economy.

In addition, we study the link between economic development and a country's ability to be close to achieving the UN Sustainable Development Goals. We then estimate the two discount rates, consumption and environmental, as a function of an Environmental Performance Index (EPI), a composite index encompassing 24 indicators that shows how far countries have come in achieving the SDGs.

From the correlation between EPI and GDP we estimate δ, which expresses the elasticity of environmental quality to variations in g_1. δ derives from the slope of the EPI-GDP regression line and influences both the value of r_c and r_q.

Once the logic of the probabilistic model has been defined, first the Environmental Performance Index is described; then the mathematical steps necessary to estimate the consumption and environmental DDRs are detailed; finally, we estimate for the first time declining consumption discount rates and declining environmental discount rates for Italy based on empirical data.

3.1 Model Operating Phases

Figure 1 shows the sequence of mathematical steps on which the model is based. This section details the assumptions and elaborations to be carried out for each step.

Step 1. *Estimation of economic parameters ρ and η_1.*

With reference to the pure time preference rate ρ, we agree with Stern (2007). The author argues that, when considering long-term public projects, it is more convincing to associate ρ with the probability of collective extinction rather than the mortality rate. Thus, we assume $\rho = 0.1\%$, i.e. we admit that there is almost a 10% chance of extinction by the end of a century. On the one hand, this value might seem high: if it were true, the human race would not have lasted so long. On the other hand, however, the value also considers the possibility of a partial extinction by an exogenous or anthropogenic force such as a nuclear war or a devastating pandemic that manages to "eliminate" a significant portion of the world's population (Stern 2007).

Considering that since the publication of the Stern Review (2007) until today, the environmental conditions of our planet have significantly worsened, a sensitivity analysis of the results could also be developed with higher ρ values ($\rho = 0.15$; $\rho = 0.20$). However, we consider it consistent overall to consider a value of 0.10%, as this gives a lot of weight to future generations and thus to climate change. η_1, the elasticity of the marginal utility of consumption: «determines how fast marginal utility falls as income rises» (Heal 2009, p.291). Groom and Maddison (2019) find that the equal-sacrifice income tax approach together with the Euler equations approach, Frisch's additive preference approach and risk aversion in insurance markets are valid approaches to estimating an η_1 value which can also be used when one wants to assess the long-run SDR.

As Groom and Maddison (2019) suggest and as discussed in the previous section, no approach is without criticism. However, we deem it consistent to use in this study or the equal-sacrifice income tax approach both because the extent of progressiveness in a country's personal income tax rates can be viewed as a reflection of the government's degree of aversion to income inequality (Evans 2005); and because it is a widely tested method as it is easy to implement. According to Cowell and Gardiner (1999), tax decisions are decisive for equalization, also about the "discount" or the "determination of social weights". Consequently, the evaluation of η_1 on the basis of the analysis of the progressive fiscal system of the country, is capable of expressing the behavior of the Government to the inequality of income distribution (Nesticò and Maselli 2020b). Cowell and Gardiner (1999) propose the following formula to estimate η_1:

$$\eta_1 = \frac{\ln(1-T')}{\ln\left(1-\frac{T}{Y}\right)} \tag{6}$$

in which *T'* equals the marginal rate; *T/Y* represents the mean tax rate.

Step 2. *Estimation of EPI and environmental parameters η_2 and δ.*

In the proposed model, the Environmental Performance Index (EPI) is used as a proxy variable to assess environmental quality. With UN's 2015 Sustainable Development Goals, more and more often governments are being asked to measure their environmental behaviour through quantitative parameters. This is because the use of empirical approaches helps to identify issues, track trends, point out policy successes and failures, identify best practices and optimize returns on investment in environmental protection (Wendling et al. 2018). Within this framework, EPI provides a measurement of a nation's sustainability and environmental performance, allowing to understand which countries implement policies useful for containing environmental pressures.

The EPI is a composite index that collects 24 individual metrics of environmental performance, which are combined into a hierarchy of ten thematic categories. These categories of problems meet two policy objectives: environmental health and ecosystem vitality. The final EPI value falls in the range 0–100, with 0 indicating the worst and 100 the best performance. Table 1 shows the hierarchical organization of the EPI, the indicators that make it up and the relative weights. In our model, we accept the weights suggested by Wending et al. (2018). The authors specify that the weights used reflect "a mixture of emphasis determined by best subjective judgement, data quality and analysis of global trends" and that in favour of transparency at each level of aggregation they calculated the resulting weight as a simple weighted arithmetic average of the weights of the lower-level indicators.

In summary, EPI provides important information on a country's environmental performance that can help refine policymaking, understand the drivers of environmental progression and maximize the return on public investment (Wendling et al. 2018). Thus, in addition to strictly financial parameters, EPI will also influence SDR estimation through the parameter δ, and consequently, environmental investment choices.

Table 1 The environmental performance index (Source: Wendling et al. 2018)

Policy objective	Weight (%)	Issue category	Weight (%)	Indicator	Weight (%)
Environmental health	40	Air quality	26	Household solid fuels	10.4
				$PM_{2.5}$ exposure	7.8
				$PM_{2.5}$ exceedance	7.8
		Water & sanitation	12	Drinking water	6.0
				Sanitation	6.0
		Heavy metal	2	Lead exposure	2.0
Ecosystem vitality	60	Biodiversity & habitat	15	Marine protected areas	3.0
				Biome production (National)	3.0
				Biome production (Global)	3.0
				Species production index	3.0
				Representativeness index	1.5
				Species habitat index	1.5
		Forests	6	Tree cover loss	6.0
				Fish stock status	3.0
		Fisheries	6	Regional marine trophic index	3.0
				CO_2 emissions–total	9.0
				CO_2 emissions–power	3.6
		Climate & energy	18	Methane emissions	3.6
				N_2O emissions	0.9
				Black carbon emissions	0.9
		Air pollution	6	SO_2 emissions	3.0
				NO_x emissions	3.0
		Water resources	6	Wastewater treatment	6.0
		Agriculture	3	Sustainable nitrogen management	3.0

The calibration of δ depends on how we define environmental quality. In fact, δ expresses how sensitive environmental quality q is to variations in consumption c, where this consumption can be approximated to GDP per capita (Gollier 2010; 2011).

Let us consider approximating c and q of assumption (ii) to a country's GDP per capita and relative EPI respectively. Applying OLS estimation of the regression coefficients, we obtain a relation of the type:

$$\ln q = a + \delta \cdot \ln c + \varepsilon \tag{7}$$

In (7) a is the line intercept on the order and ε the statistical error of the regression.

The degree of aversion to environmental risk η_2 is not always easily assessed. Gollier (2010, 2011) points out that the percentage of consumption expenditure to be assigned to environmental quality is provided by the below formula:

$$\eta^* = \frac{\eta_2 - 1}{\eta_1 + \eta_2 - 2} \tag{8}$$

Some authors suggest deriving the value of η_2 in (11) assuming η^* is between 10 and 50% (Hoel and Sterner 2007; Sterner and Persson 2008). Gollier (2010), for instance, accepts $\eta^* = 30\%$, from which a value of $\eta_2 = 1.4$ is derived.

Step 3. *Probabilistic forecast of the* r_c *and* r_q.

The new idea concerns the modelling the parameter g_1 in (4) and (5) as an uncertain variable during the study period. In other words, it is necessary to associate to the unknown future value of g_1 a probability distribution deduced from the historical trends g_t in a sufficiently wide past time span.

Once the distribution of the probable values of g_1 is predicted based on the historical trend analysis, it is possible to obtain the probability distribution of the discount rate r_c of consumption and the discount rate r_q of environmental quality. This can be done by implementing the Monte Carlo analysis, a stochastic simulation method based on random sampling. Through this method, it passes from the probability distribution of the uncertain variable, that is g_1, to the probability distribution of the two discount rates: r_c and r_q, that are correlated to the growth rate of consumption through (4) and (5).

Step 4. *Estimation of discount rates declining consumption* r_{ct} *and environmental* r_{qt}.

Having obtained the probability distributions (step 3), we derive the expected values of r_c and r_q values for each instant of the study period.

In fact, according to the logic of ENPV approach, estimating the Expected Net Present Value with an uncertain but constant discount rate is equivalent to calculating the Net Present Value with a certain but decreasing rate with a "certainty-equivalent" approaching the minimum possible value at time equal to ∞ (Newell and Pizer 2003). According to this approach, passing from the uncertain and constant discount rate to a certain but declining discount rate it is possible assessing the "certainty-equivalent" consumption discount factors F_{ct} and "certainty-equivalent" environmental discount factors F_{qt} for each future instant t. The following two formulas make it possible to estimate F_{ct} and F_{qt}:

$$F_{ct} = \sum_{i=1}^{m} p_{rci} \cdot e^{(-r_{ci} \cdot t)} \tag{9}$$

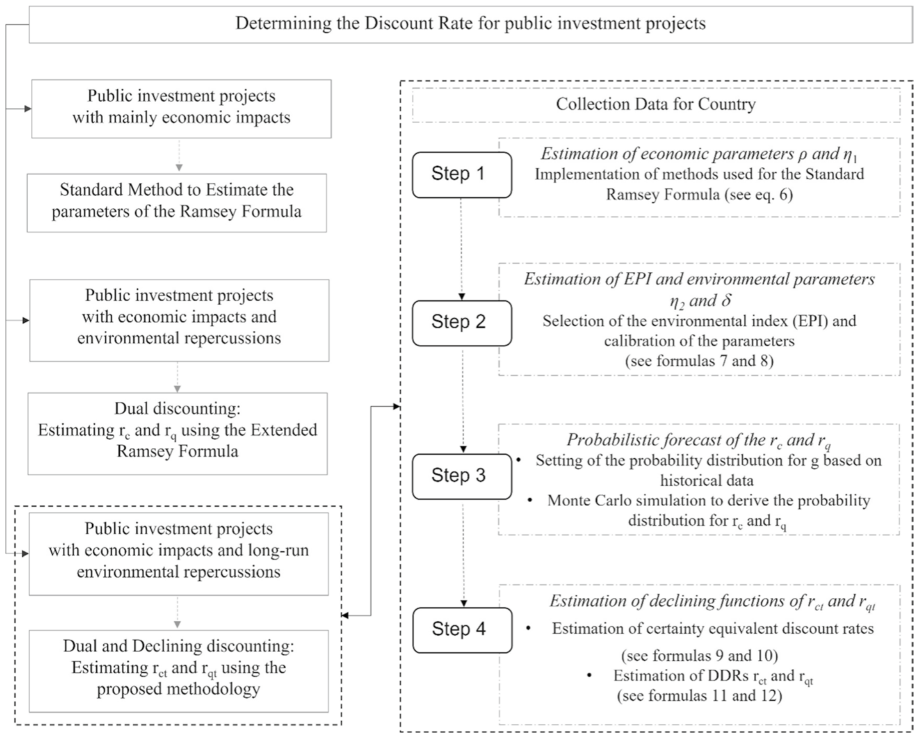

Fig. 2 Flow chart for determining consumption discount rates and environmental discount rates

$$F_{qt} = \sum_{i=1}^{m} p_{rqi} \cdot e^{(-r_{qi} \cdot t)} \tag{10}$$

where:

r_{ci} = ith consumption discount rate value, resulting from the probability distribution of r_c returned by (4) in which g_1 is assumed as uncertain variable;

p_{rci} = probability vector of r_{ci};

r_{qi} = ith environmental discount rate value, resulting from the probability distribution of r_q returned by (5) in which g_1 is assumed as uncertain variable;

p_{rqi} = probability vector of r_{qi};

t = time;

m = intervals of discretization of probability distributions r_c and r_q.

At this point, starting from the time sequences obtained from (9) and (10), the two discount rates r_{ct} and r_{qt} are estimated:

$$r_{ct} = \frac{F_{ct}}{F_{ct+1}} - 1 \tag{11}$$

$$r_{qt} = \frac{F_{qt}}{F_{qt+1}} - 1 \tag{12}$$

Table 2 Income tax structure for Italy

Gross annual taxable income	Number of taxpayers (%)	Marginal tax rate (%)	Mean tax rate at the midpoint of the income bracket (%)
up to 15,000 euro	44.53	23	23.00
from 15,000 to 28,000 euro	34.67	25	23.60
from 28,000 to 50,000 euro	15.25	35	27.05
over 50,000 euro	5.55	43	38.94

Table 3 Estimation of η_1 in the midpoint of taxable income brackets

Taxable gross annual income bands (euro)	0–15,000	15,000–28,000	28,000–50.000	> 50,000
Average value of the range	7,500	21,500	39,000	175,000
Marginal tax rate (*T*')	23%	25%	35%	43%
Mean tax rate (*T*/*Y*)	23.00%	23.60%	27.05%	38.94%
ln (1—*T*')	−0.261	−0.288	−0.431	−0.562
ln (1—*T*/*Y*)	−0.261	−0.269	−0.315	−0.493
η_1	1.00	1.068	1.366	1.139
% of contributors	44.53%	34.67%	15.25%	5.55%
$\eta_{1\text{weighed}}$	1.087			

To make this procedure holistic and easier to implement in practice, we structure a flow chart (Fig. 2) whose objective is to understand when and how to apply the defined methodology to determine consumption and environmental discount rates. It is a procedure that can be applied to any consumption context. Below is the application for Italy.

4 Calculation. The Estimation of the DDRs for Italy

In this section, an empirical estimate of the consumption and environmental DDRs for Italy is provided. We first want to show that dual and declining approaches are necessary for the assessment of projects with long-term environmental effects, and that the estimation is based on data rather simple to obtain. Therefore country-specific estimates should be provided. The elaborations retrace the operational steps of the proposed model, summarised in Figs. 1 and 2.

Step 1. *Estimation of economic parameters* ρ *and* η_1.

As discussed in Sect. 3.2, we agree with Stern (2007) on the evaluation of the pure time preference rate. Since we consider long-term public projects, it is more convincing to associate ρ with the probability of collective extinction rather than the mortality rate. Therefore, we assume $\rho = 0.1\%$, assuming that there is almost a 10% chance of extinction by the end of a century. η_1 is estimated by implementing the formula (6). The starting point is Italy's income tax structure shown in Table 2. The marginal tax rates are in effect from 2022, while the number of taxpayers by successive brackets of total income is relative to

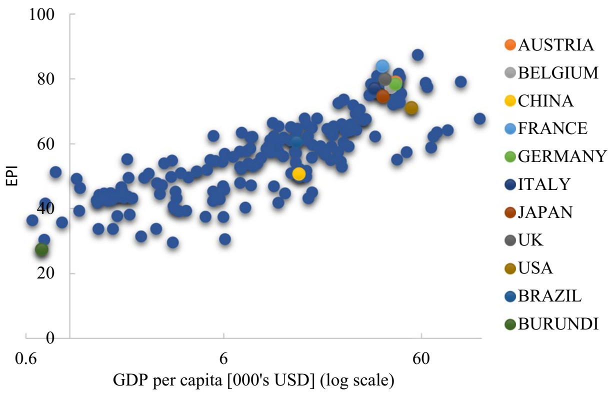

Fig. 3 The relationship between EPI and GDP per capita

the 2020 tax year based on 2021 declarations (data from Department of Finance, Ministry of Economy and Finance).

Table 3 shows the values of η_1, estimated based on the marginal tax rate, different for each income bracket, and the average tax rate calculated at the middle value of the income bracket.

The weighted average of the elasticity value for Italy is obtained by assigning weights to the different η_1 according to the percentage of taxpayers falling in the specific income bracket. The estimated value is lower than the estimates obtained from the literature, which average around 1.5. This is mainly attributable to the fact that in Italy only 15.25% of taxpayers pay marginal tax rates above 35% and only 5.5% pay rates above 43%, demonstrating in fact a low degree of 'inequality aversion' of the Italian personal income tax system.

Step 2. *Estimation of EPI and environmental parameters η_2 and δ.*

Since it has been hypothesised that environmental quality is related to consumption through a deterministic function of the type $q_t = f\,(c_t)$, it is important to analyse the correlation between EPI and the relative per capita GDP of a country. From this analysis it emerges that, in general, the achievement of sustainability goals is linked to the economic capacity to investment in the infrastructure for the protection of both human health and ecosystems. In a rapidly urbanizing world, it is essential to create facilities that provide better sources of drinking water, wastewater management and pollution mitigation. On the other hand, however, the intrinsic tension of sustainable development is that the economic growth often goes against the improvement of the environment, especially in terms of use of natural resources and uncontrolled industrialization (Wendling et al. 2018). Figure 3 shows for 180 countries that higher values of GDP per capita tend to correspond to higher values of EPI.

As regards the estimation of the two environmental parameters, the value of η_2 is derived from (8) assuming $\eta^* = 30\%$, according to Sterner and Persson (2008) and Gollier (2011). Therefore, η_2 is equal to 1.15.

δ, on the other hand, summarizes how much the environmental quality q, expressed through the EPI, is sensitive to changes in consumption c, with c approximate to GDP per capita. For 180 countries, the index values for 2018, which are the most recent, are correlated to their GDP per capita for the same year 2018. In Fig. 4, each pair of EPI-GDP values refers to a specific country. Therefore, δ represents the average EPI-GDP elasticity found with reference to the 180 reference countries. In other terms, the relationship between environmental quality and consumption is considered with reference

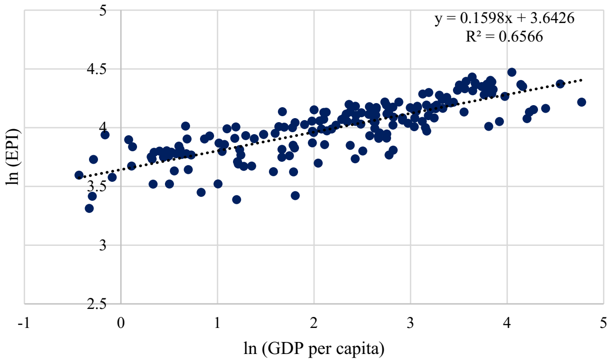

Fig. 4 The relation between EPI and GDP per capita to estimate δ

to the effects on the processes of climate and environmental change worldwide. This calibration takes up what Gollier (2010) proposed. The analysis shows a positive correlation between EPI scores and economic wealth. Figure 4 suggests the result of the regression analysis carried out according to (7), in which δ is equal to 0.16. This shows that achieving sustainability goals requires material prosperity to invest in the infrastructure needed to protect human health and ecosystems. This means that in a rapidly urbanising world, it is important to have the resources to build facilities that provide better sources of drinking water, protect ecosystem services, sustainably manage wastewater, and mitigate pollution (Wendling et al. 2018). Conversely, it is also true that income growth too often takes place at the expense of the environment, either through overexploitation of natural resources or the uncontrolled expansion of industrial facilities. Indeed, the trade-offs between environmental performance and country wealth are also blurred by trade. So far, the spillover costs of trade are poorly captured in most environmental metrics, although this is an active area of study (Sachs et al. 2017) and certainly further efforts to improve global accounting methods to achieve sustainable development goals need to be made. Certainly, the issue deserves further investigation in future studies, and we are aware that a different definition of q could lead to a different calibration of the parameter δ.

Step 3. *Probabilistic forecast of the consumption* r_c *and environmental discount rate* r_q.

According to literature data, g_t is estimated based on the per capita GDP growth rate (Percoco 2008). From the trend of per capita GDP growth rate and related economic shocks, we believe it is correct to select the data for the fifty years 1972–2021. In determining the probable values to be assigned to the consumption growth rate, it is first important to find the probability distribution that is most comparable to the starting historical time series, which in this case is the Weibull curve. Then, the probable values of the GDP growth rate are forecast by applying the Monte Carlo simulation, calibrated on 10,000 random trials. Once the probability distribution of g_1 is established, we also derive the probability distributions of the r_c and r_q. Figure 5 shows the probability distributions of g_1, r_c, r_q deriving from the Monte Carlo simulation, while the values of the statistical indices relating to the forecast are in Table 4. From the elaborations, we deduce that: $-11.87\% < g_1 < 13.81\%$ and the mean standard error after 10,000 simulations is 0.03%; $-15.74\% < r_c < 17.05\%$ and $-3.59\% < r_q < 4.07\%$. In both simulations, the mean standard error is acceptable: it is 0.03% after 10,000 tests for r_c, and 0.007% for r_q.

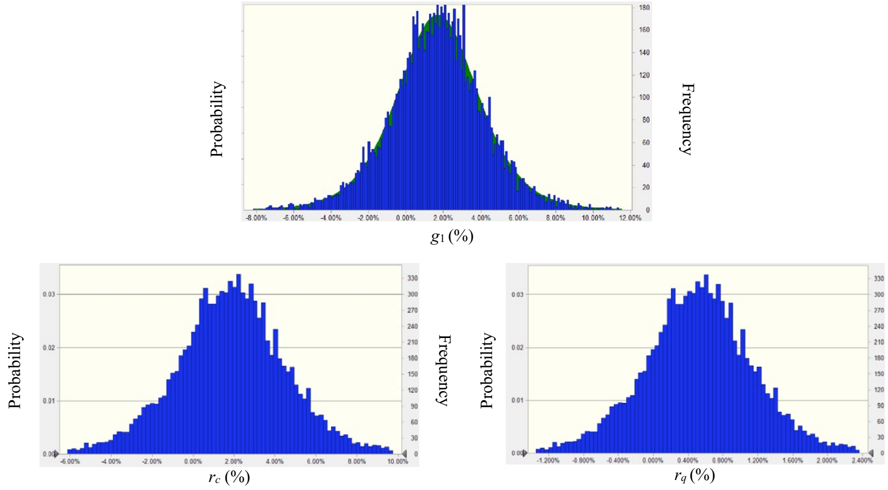

Fig. 5 Probability density function for g_1, r_c and r_q

Table 4 Statistical indices for g_1, r_c and r_q

	Hypothesis: g_1	Forecast: r_c	Forecast: r_q
Number of tests	10,000	10,000	10,000
Base case	1.59%	1.75%	0.49%
Mean	1.64%	1.89%	0.53%
Median	1.69%	1.93%	0.67%
Standard deviation	2.58%	2.88%	0.67%
Variance	0.07%	0.08%	0.0048%
Kurtosis	4.14	4.27	4.27
Coeff. of variation	1.57	1.53	1.28
Min	−11.87%	−15.74%	−3.59%
Max	13.81%	17.05%	4.07%
Mean standard error	0.03%	0.03%	0.007%

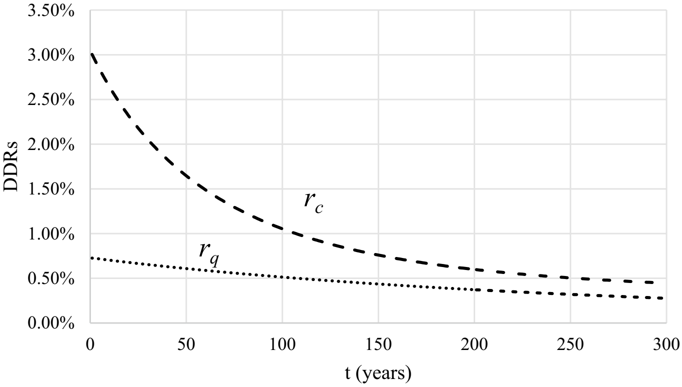

Fig. 6 r_{ct} and r_{qt} term structure for Italy

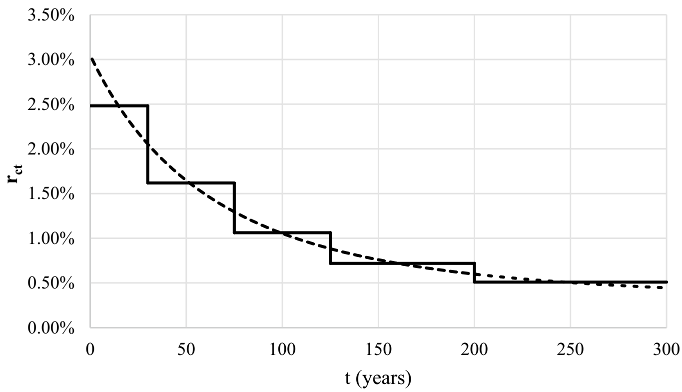

Fig. 7 Step structure for consumption discount rate r_{ct}

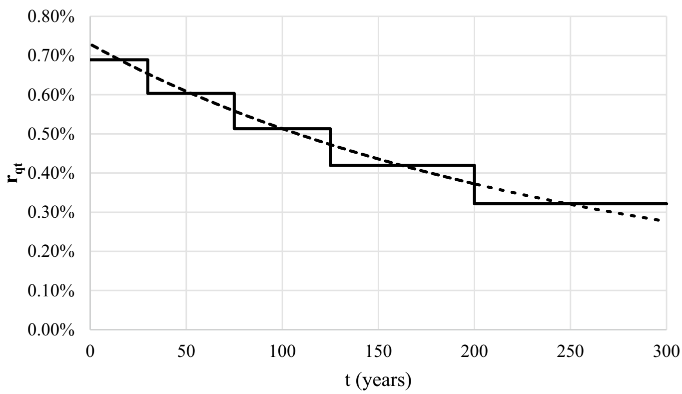

Fig. 8 Step structure for environmental discount rate r_{qt}

Step 4. *Estimation of declining functions of* r_{ct} *and* r_{qt}.

We discretize into 100 intervals the probability distributions r_c and r_q from the previous step. Then, for each interval of each of the two distributions, we assess the mean value of each interval. At this point it is calculated the certainty equivalent discount factors F_{ct} and F_{qt} (see formulas 9 and 10 introduced in the previous section). Then, we can evaluate r_{ct} and r_{qt} for each time instant (see formulas 11 and 12). These are time-declining functions. We have assumed a time horizon of three hundred years. Figure 6 shows the term structure of r_{ct} and r_{qt} for Italy.

5 Results and Discussions

The following results emerge from the elaborations:

– r_{ct} amounts to 0.45% at year t = 300 from a value of 3.00% for t = 1;

Table 5 Value of r_{ct} and r_{qt} for each step

Years	r_{ct} (%)	r_{qt} (%)
1–30	2.48	0.69
31–75	1.62	0.60
76–125	1.06	0.51
126–200	0.72	0.42
201–300	0.51	0.32

– r_{qt} assumes values markedly lower than r_{ct}, beginning from 0.73% and reaching 0.28% at the end of the analysis period.

The Green Book (HM Treasury 2003, 2020) recommends a schedule of decreasing discount rates for different categories of projects but constant in the following time intervals: 1–30 years; 31–75 years; 76–125 years; 126–200 years; 200–300 years; for over 301 years. In this way, it is simpler for operators to develop the calculations: applying a constant SDR value in the single time interval, instead of using different values from year to year, certainly makes the Cost–Benefit Analysis easier. Following the time intervals suggested by Green Book (2003), we define step functions for r_{ct} and r_{qt}. Figures 7 and 8 give the results obtained. Table 5 gives details of the values taken by the two discount rates, consumption and environmental, in each step.

Averaging the data obtained for the first 30 years, we have an SDR of 2.5%. This is lower than that suggested by the European Commission, which is 3.0%. The environmental discount rate for the entire assessment period is lower than the consumption discount rate. This highlights the need to use dual discounting also for projects with intergenerational effects. In fact, the environmental discount rate for the first 30 years is 0.7%. In the case of projects with long-term effects, using dual and declining discounting should be the most appropriate choice. It is evident that the use of the constant discount rate of 3.0% suggested by the European Commission leads to a much lower estimate of the Net Present Value (NPV) than would be obtained by using the estimated consumption and environmental discount rates. In other words, using the 3.0% discount rate would underestimate environmental damages and benefits progressively further out in time.

6 Conclusion

In Cost–Benefit Analysis (CBA), discounting is a crucial operation to properly take into account both economic, environmental and social impacts of public investment strategies. Experts are aware that the discount rate is a key parameter to guide the valuation of stocks and projects with long-lasting impacts. Indeed, companies with a low discount rate give more importance to the future than companies with a higher discount rate. Thus, the discounting strategy in the public sector (but also in the private sector) becomes the key factor for capital allocation. This allocation is in turn a key factor in economic growth. However, there is no consensus in the literature on the question and which discount rate should be used in the analysis. In addition, with the incessant increase in environmental stress, conventional discounting procedures—i.e. based on constant rates—are inappropriate, particularly when intergenerational environmental aspects have to be considered in *ex ante* economic evaluation. In such circumstances, we believe that the combined use of declining discounting and dual discounting can guide the analyst towards the selection of sustainable investment alternatives.

The study's purpose is therefore to develop a model for estimating the consumption discount rate and the environmental discount rate, both with a declining structure over time. Such discount rates will therefore be necessary to evaluate investment strategies with long-term environmental and economic effects. The main innovations of the model are two: (1) the growth rate of consumption g_1 is modelled as a stochastic variable. This means that from the historic trend analysis of g_1, a probability function to be associated to the parameter itself is first estimated. Then, by implementing the Monte Carlo analysis, the probability distribution to be associated to the consumption discount rate r_c and the environmental discount rate r_q is estimated with the aim of considering macroeconomic risk. In this way, i.e. taking into account the intrinsic uncertainty of the growth rate of consumption and thus of the economy, we obtain declining functions for the two discount rates (r_{ct} and r_{qt}). This is possible by switching from a constant but uncertain discount rate to a certain but declining discount rate with an equivalent certainty; (2) Environmental Performance Index (EPI), which makes it possible to establish how close countries are to achieving the UN's Sustainable Development Goals, is used as a proxy variable to estimate environmental quality.

The following results emerge from the application: r_{ct} has an initial value of 3.00% and decreases to 0.45% after 300 years; r_{qt} is 0.73% at time $t=0$ and decreases to 0.28% at the end of the evaluation period. It is deduced that environmental quality is a more uncertain parameter than the growth rate of consumption. From here we have that $r_{qt} < r_{ct}$.

The results of the processing show how the use of dual and declining discounting or, alternatively, constant discounting significantly changes the result of a cost–benefit test. In fact, in the former case, the environmental effects that are progressively more distant in time are given greater weight than those assigned to the financial components. In other words, the use of conventional discounting procedures, i.e. based on time-invariant discount rates, would lead to choices that are not always efficient. This is because the analyst, on the one hand, would neglect alternatives whose benefits have been felt by later generations than those that have implemented them; on the other hand, he would focus on investments with high initial returns, but with long-term environmental repercussions.

With this research we want to demonstrate the necessity of applying in practice alternative discounting procedures to the traditional ones. The estimation of discount rates for Italy highlights the practical applicability of the proposed model and the need to conduct country-specific evaluations of discount rates. In fact, the policy implications that the implementation of the proposed model may have on the whole environmental decision-making process are extremely important.

The next step of the research is to test the model also for other economies and to specify it also for different sectors (e.g. water, energy, health). This can be done by calibrating environmental parameters differently, environmental risk aversion and the elasticity of environmental quality with respect to consumption. The idea is to first estimate consumption discount rates and environmental discount rates for different countries; then to collect all the necessary data to define a database containing discount rates (consumption and environmental) for government projects for different economies (advanced and emerging) and sectors. With this database it will be easy to run simulations to examine the robustness of the calculated discount rate to various changes in the parameters setting. It will be a useful decision support tool to determine and compare the discount rate for countries and economic sectors.

Author contribution Nesticò and Ulgiati contributed to the study conception and design. Material preparation, data collection and analysis were performed by Ghisellini, Maselli, and Nesticò. The first draft of the manuscript was written by Maselli and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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