Embedding Preference Uncertainty for Environmental Amenities in Climate Change Economic Assessments: A "Random" Step Forward

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Abstract: While there is a considerable debate regarding the choice of proper discount rates for assessing climate change projects and policies, only a tiny body of literature emphasizes "what to discount". Usually, climate change economic assessments rely on tools and methods that employ strong simplifications, assuming, among others, given and fixed preferences about the values of man-made and environmental goods. Aiming to fill a gap in the literature, this paper leaves aside the issue of discounting and focuses on the nature and impact of preference uncertainty on the economic estimates of future climate change damages on ecosystem non-market goods and services. To this end, a general random walk-based stochastic model is proposed, combining a number of parameters, e.g., the growth of income, depletion of environmental assets, the elasticity of income and demand, and the change in preferences towards the environment. The illustrative application of the model shows that the value of environmental losses is significantly affected by the change in preferences. By doing so, the model allows the analyst to visualize future paths of preference evolutions and to bring future values of damaged environmental assets realistically to the fore. If these elements are neglected when estimating climate change-related future damages to environmental goods and services, the results may be too narrow from a policy perspective.

1. Introduction

Present policies that aim at addressing issues in health, insurance, education, infrastructure, space exploration, etc., have impacts that frequently extend into the far future. In that sense, current policies impinge on the welfare of future generations above and beyond that of present constituencies. Policy response to climate change provides a very striking example. Climate change is profoundly about the future; mitigation and adaptation policies are impacting future generations, and to a lesser degree the present one, meaning that present costs should be weighed against future benefits. Much of the literature related to climate change—and other projects or policies whose costs and benefits extend

into the future—focuses on the choice of proper discount rate on the basis of which future benefits are made comparable to present costs, e.g., (Cline 1992; Arrow et al. 1996; Dasgupta et al. 1999; Dasgupta and Maskin 2005; Stern and Cabinet Office—H.M. Treasury 2007; Stern 2008; Nordhaus 2007; Dasgupta 2008; Gollier 2008; Weisbach and Sunstein 2008; Heal 2009; Baum and Easterling 2010; Scarborough 2010; Gollier and Weitzman 2010; Kaplow and Weisbach 2011; Vale 2016). The debate regarding the appropriate social discount rate is reflected, among others, in the choice of the pure social rate of time preference (usually denoted by δ) and the elasticity of marginal utility of consumption (usually denoted by η). For instance, Nordhaus (2007) uses $\delta = 1.5$ and $\eta = 2$, Stern's (Stern and Cabinet Office—H.M. Treasury 2007) choices are $\delta = 0.1$ and $\eta = 1$, and Weitzman (2007) specifies $\delta = 2$ and $\eta = 2$, respectively. Employing different consumption growth forecasts may further widen the distance between the discount rates, resulting in staggering differences when discounting over long periods of time.

The debate on discounting future costs and benefits is fascinating from a philosophical and economic perspective. It makes our attitudes toward future generations explicit and strengthens the need for rational and well-informed policy advice. It is, however, surprising that the ongoing discussion on "how to discount" is not matched with an analogous discussion on "what to discount". To clarify ideas, researchers and policy-makers have relied heavily on integrated assessment models (IAMs) to explore the pathways through which greenhouse gas emissions accumulate in the atmosphere and oceans, and to assess natural impacts and economic consequences (Metcalf and Stock 2015; Bosello 2014). The monetized impacts of climate change, known as social cost of carbon (SCC), are used by national agencies and/or international organizations in cost-benefit analyses of climate change regulations and programs (Watkiss and Hope 2011). Nevertheless, subsequent critiques have challenged the findings of IAMs arguing that the models employ strong simplifications and use weakly defended assumptions; the socio-economic scenarios usually under-sample the range of plausible futures; the models do not incorporate emissions of any greenhouse gas other than carbon dioxide; etc., e.g., (Sterner and Persson 2008; O'Neill 2010; Warren et al. 2010; Masur and Posner 2011; van Vuuren et al. 2011; Hof et al. 2012; Kopp and Mignone 2012; Metcalf and Stock 2015; Pindyck 2013; Balint et al. 2017).

The cautious reader is puzzled by the list of limitations mentioned above. Yet, there are even more issues that need to be considered when estimating climate change-related future damages to environmental goods and services (e.g., Lee et al. 2015; Balint et al. 2017). The value of environmental goods and services is often underestimated or taken for granted, since markets are usually unable to provide an appropriate unit of account, e.g., (Hein et al. 2006; Boyd and Banzhaf 2007; Fisher et al. 2009). As Sterner and Persson (2008) conclude after modifying DICE model to account for environmental scarcity:

> " ... *Even if the climate damages in the DICE model used in the numerical exercise above are doubled to account for a wider range of nonmarket impacts, following the results in the Stern Review, we would argue that these impacts are still comparatively low ...* "

> "*We believe that it is exactly the nonmarket effects of climate change that are the most worrisome. If we focus on the risk for catastrophes, as Weitzman suggests, then we believe the main effect of climate change will not be to stop growth in conventional manufacturing, but rather to damage our ability to enjoy some vital ecosystem services ...* "

More specifically, there are two key issues; namely, (a) the (tacit) assumption of perfect substitutability between man-made and environmental goods and services (Neumayer 1999) and, accordingly, the calculation of environmental damages predominantly on the basis of market goods (i.e., on a GDP basis through a reduction in the consumption of market goods and services); and (b) the (tacit) assumption that future environmental values do not diverge from present ones. These assumptions raise in turn further questions on models' capacity to tackle issues such as the uncertainty surrounding the evolution of markets, changes in consumption modes and habits, future generations' own preferences, and accordingly the influence of future preferences on the monetary estimation of future environmental

damages. Despite the relevant literature regarding these issues, e.g., (Horowitz 2002; Ayong Le Kama and Schubert 2004; Hoel and Sterner 2007; Sterner and Persson 2008; Jacobsen et al. 2013; Ackerman and Stanton 2013) most of the economic assessments relating to climate change damages are silent about the potential impact of preference uncertainty on the estimates and how it could be taken into consideration.

This paper, leaving aside the issue of discounting, aims to add to the limited literature on the effect of preference uncertainty on the economic estimates of future climate change damages and in particular on the value that people place on environmental goods and services. For this purpose, a number of parameters, e.g., the growth of income, the depletion of environmental assets, and the change in preferences towards the environment, are explored and combined in a stochastic framework as a general random walk-based model, in order to simulate the growth rate of the non-market value for an environmental good or service.

The rest of the paper is structured as follows: Section 2 sets the scene about the problem of preference uncertainty with a particular focus on the value of non-market goods and services. Section 3 details the theoretical and methodological aspects of the model. Section 4 presents an illustrative example of the proposed approach. Finally, Section 5 summarizes conclusions and recommendations.

2. Framing the Problem of Future Preference Uncertainty

Present generations invest in climate change adaptation and mitigation for two reasons: an ethical one, meaning a moral sense of responsibility toward the yet unborn; and a rights aspect, meaning that posterity has as much rights as we did to inherit a hospitable Earth (Summers and Zeckhauser 2008). Whatever the reason may be, our attitude toward posterity is either guided by our own preferences and thus contemporary patterns of relative social worth of man-made and ecosystem assets. In this case, we exhibit a paternalistic altruism to future generations. Or, alternatively, we take future preferences seriously and conjecture as to what would future generations themselves consider a welfare-enhancing pattern of man-made and ecosystem assets. This is a non-paternalistic attitude to future generations (Horowitz 2002).

Despite the nature of motives behind climate change policies, analysts (implicitly or explicitly) extend present preferences (derived from market transactions or inferred through stated preference measures) into the future by calculating all damages in prices of a base year, using the price level of the base year as the basis for aggregation (Anderson et al. 2012; Noblet et al. 2015). This is not surprising considering that the neoclassical model traditionally explores theoretical and empirical problems considering preferences as fixed and given (Janssen and Jager 2001). Yet, this view ignores potential changes in preferences and, accordingly, relative values of man-made and environmental goods. For instance, if—in terms of weak sustainability—future generations were richer in material goods but less equipped with environmental amenities, the relative prices could shift, making environmental amenities more valuable than today. That, in turn, would substantially reinforce the value magnitude of the physical loss of non-market goods, possibly counterbalancing the rise in the value of the aggregated man-made assets.

The causes behind the uncertainty of future preferences are well established in the literature. For instance, consumer preferences are influenced by the social setting in which the product is being used (i.e., the preference may be affected by who else uses this product); the proportion of people in the actor's social network that consumes this product (the so-called "socialization effect"); and the intensity of preference for a product that is repeatedly being consumed (a process known as "exposure effect") (see Janssen and Jager 2001 for a detailed discussion). In addition, preference uncertainty may be related to overconfidence in forecasting individual future preferences that lead to errors in predictions of future consumption (Thunström et al. 2015). Uncertainty of future preferences is also attributed to incorrect predictions of feelings that have been found to impact consumer behavior, e.g., (Loewenstein and Schkade 2003; MacInnis et al. 2005).

When it comes to environmental amenities in particular, preference uncertainty may be explained by the random state of nature, the uncertainty of future income, or the unfamiliarity with the good (Thunström et al. 2015). To wit, the non-market value refers to small changes in the state of the environment and not the state of the environment itself (TEEB 2010). The estimates are based on people's willingness-to-pay (WTP)—the maximum amount of money in order to avoid an environmental degradation and its consequences on health, amenity, etc.,—or their willingness-to-accept (WTA)—the minimum compensation in order to endure the environmental impacts incurred (Freeman 2003). In this regard, the value of environmental assets is individual-based and subjective, as well as context- and state-dependent (Goulder and Kennedy 1997; Nunes and van den Bergh 2001; Kontogianni et al. 2010). Hence, the estimates of non-market values reflect only the current choice pattern and are affected by socio-economic-ecological conditions such as the state of the environment, the available income, attitudes (e.g., voluntary participation in activities to protect the environment), opinions and beliefs, and expectations about the future (Barbier et al. 2009; Besley and Persson 2019; Lamb 2019; Pingali et al. 2019). It is evident that a change in socio-economic-ecological conditions might severely affect the estimated values (TEEB 2010).

Despite extensive literature on the topic of preference uncertainty, it is evident that there is a dearth of study on how to account for the effect of changing preferences on the economic estimates of future climate change damages.

3. Methodology

3.1. Model Considerations

Our model builds upon an early work of Fisher and Krutilla (1975) with respect to changing values for the environment, i.e., the growth rate of the WTP value for an environmental good or service, but it goes a step further by incorporating new factors and employing stochastic random walk-based simulations, as detailed later. Fisher and Krutilla (1975) suggested that evolving preferences at time t (i.e., WTP_t) could be captured by the continuous stream of the "present" WTP (i.e., WTP_0) for the environment flowing at some pre-determined rate, say α:

$$WTP_t = WTP_0 e^{\alpha t} \tag{1}$$

where

WTP_0 is the present WTP for an environmental good or service.
WTP_t is the future WTP for the environmental good or service at time t.
α is the growth rate of the WTP value for the environmental good or service.
t is the time in years (assuming that α and discount rates are expressed on a yearly basis).

The present value (PV) of WTP_t, assuming a social discount rate s and continuous compounding, is estimated as follows:

$$PV_{WTPt} = WTP_0 e^{\alpha t}/e^{st} \text{ or } PV_{WTPt} = WTP_0/e^{(s-\alpha)t} \tag{2}$$

The issue of non-constant WTP values is acknowledged and then left aside, e.g., (Sterner and Persson (2008) providing examples from Arrow et al. (1996); Nordhaus (1997); Lebègue et al. (2005); Gollier (2007)). Therefore, current IAMs create the feeling that the economic damages due to the effects of climate change are being trivialized (Parry et al. 2001).

According to Fisher and Krutilla (1975) and Horowitz (2002), two factors are likely to determine the growth rate of WTP, which is the focus of this paper: the growth of income and changes in environmental quality (i.e., resource scarcity). Further, and as mentioned previously, WTP values are influenced by the substitution elasticity between natural and man-made capitals, e.g., (Krysiak and Krysiak 2006; Hoel and Sterner 2007; Sterner and Persson 2008) and by the attitude of future

generations towards environmental assets (Ayong Le Kama and Schubert 2004). These factors are discussed in more detail below.

3.1.1. Income Growth

The increase in WTP values owing to the growth of income depends on income elasticity of demand (Gravelle and Smith 2000; Horowitz 2002; Groom et al. 2005). The literature provides some evidence regarding the income elasticity of demand for environmental assets, e.g., (Borcherding and Deacon 1972; Bergstrom and Goodman 1973; Thomas and Syme 1988; Dalhuisen et al. 2003; Hökby and Söderqvist 2003; Worthington and Hoffman 2008; Yoo et al. 2014). Income elasticities of demand vary significantly from 0.01 up to 7.8; however, the majority of the estimates are less than 1. In general, estimates of the income elasticity of demand are difficult to derive from non-market valuation studies because contexts in which varying price and quantity combinations are seldom considered. This is the reason why what is usually observed is the income elasticity of WTP, which is estimated as follows:

$$\omega = \frac{\partial WTP}{\partial Y} \frac{Y}{WTP} \qquad (3)$$

where

Y is the income.
WTP is the willingness to pay amount.

The relationship between the income elasticity of demand and the income elasticity of WTP is not predetermined, as an environmental good may have income elasticity of demand greater than 1 and income elasticity of WTP greater or less than 1 (Flores and Carson 1997). Several empirical studies suggest that WTP is an increasing function of income (Kriström and Riera 1996), i.e., respondents with more income tend to express higher WTP values for environmental improvements; that is, environmental improvements are typically normal goods. Yet, this is not always the case. Pearce (2003) discusses a general conceptual framework for the analysis of the distribution of environmental costs and benefits using the available empirical literature. As Pearce (2003) points out, with some exceptions the income elasticity of WTP for environmental quality is less than 1. Similar conclusions are drawn also from Jacobsen and Hanley (2009), while Martini and Tiezzi (2014) estimated income elasticities between 1.165 and 1.345, suggesting that as societies get richer they tend to value environmental quality more highly.

3.1.2. Environmental Scarcity

The scarcity of environmental goods and services will likely increase future WTP for environmental goods assuming a negative price elasticity of demand. Nevertheless, the price elasticity of demand for environmental amenities cannot be estimated directly since welfare estimates are usually derived from the indirect utility function. The literature provides several studies that attempt to estimate price elasticities of environmental assets. Not surprisingly, the majority of them deal with environmental resources that can be easily deemed as market goods, e.g., residential or irrigation water (e.g., Thomas and Syme 1988; Hewitt and Hanemann 1995; Pint 1999). Arbués et al. (2003) examine differences in the specification of water demand models and analyze several tariff types and their objectives through an extensive literature review. Worthington and Hoffman (2008) also provide a synoptic survey of empirical residential water demand analyses conducted in the last 25 years. Price elasticity estimates are generally found in the range of 0 to 0.5 in the short run and 0.5 to 1 in the long run (in absolute terms). Borcherding and Deacon (1972) explored the parameters that govern the demand of public services in the U.S. for various public goods, including parks and recreation. The results show price elasticities of demand to be less than one in absolute terms. Bergstrom and Goodman (1973) estimated that the price elasticity of demand for parks and recreation is higher than 1 (~1.13) on absolute terms. Rosenberger and Stanley (2010) conducted a meta-regression analysis of own-price

elasticity of recreation demand estimates in the U.S. The raw average elasticity is unitary (−0.997), while the median elasticity is inelastic (−0.567). Finally, Hökby and Söderqvist (2003) found price elasticity of demand equal to −1.86 (95% confidence interval: −2.08, −1.64).

3.1.3. Substitution Elasticity between Natural and Man-Made Capitals

As mentioned by Sterner and Persson (2008), who provide a detailed analysis on the subject, when non-market goods are perfectly substitutable with market goods, non-market damages can be included in consumption directly. However, when there are limits to the substitutability between market and environmental goods (i.e., when elasticity of substitution is less than 1), WTP would be expected to rise with increasing scarcity. Similar results are reported by Hoel and Sterner (2007). In addition, Krysiak and Krysiak (2006) note that for constant nature and capital stocks, an increase in the elasticity of substitution increases the absolute change in the maximal stock of nature at which a further reduction is not sustainable to counter a decrease in the level of sustainability. Hence, they argue that substitution possibilities and uncertainty about future preferences (or production possibilities) are substitutes in the sense that an increase in the uncertainty about future preferences can be compensated by a lower elasticity of substitution, and vice versa. As a result, more uncertainty provides a rationale for more preservation (Fisher and Krutilla 1975).

Although the elasticity of substitution has significant implications with respect to future WTP values, risk aversion and discount rates (Ayong Le Kama and Schubert 2004; Krysiak and Krysiak 2006; Traeger 2007), it is hard to provide good empirical estimates for the elasticity of substitution. The elasticity of substitution varies considerably among environmental goods and services, as well as between individuals (Sterner and Persson 2008).

3.1.4. Changing Preferences

Future WTP values will be affected by the attitude of future generations towards environmental assets. Their attitude may well be different from ours for many reasons, some of which are obvious, and others unpredictable since the formation of preferences involves complex and interlinked economic, social and moral determinants (Ayong Le Kama and Schubert 2004; Grüne-Yanoff and Hansson 2009). This diversification of the perceptions among generations can be considered both conspicuous and unpredictable. A change in preferences may occur in the future unexpectedly, while it can affect the level of utility associated with the level of consumption of the examined environmental goods.

Two different behaviors can be expected due to changes in preferences. Firstly, if both economic growth and environmental quality are considerably low, people will tend to be more provident and conservative. However, in a case where economic growth is high and environmental quality fair, people will increase the existing levels of consumption despite the deterioration of environmental quality adopting a type of insurance behavior against future conditions. As a result, estimating changes in preferences depends on present concerns about the well-being of future generations and requires the estimation of both the living conditions and the corresponding preferences in the future. Therefore, assumptions about the impact of present actions on the future living conditions and the respective changes of preferences are required for the analysis of changing preferences (Krysiak and Krysiak 2006).

There are good reasons to suspect that future people will care more about the natural environment (greening of preferences), leading to higher WTP values. Indisputably, the deterioration of the existing quality of the environment in combination with the upcoming depletion of the natural sources constitutes the main reason for this tendency. Yet, this is not definite. Ayong Le Kama and Schubert (2004) argue that future generations may value environmental goods and services less than the present one. To illustrate this, the authors analyze changes of future preferences which lead to a more conservative utilization of the natural resources, assuming that environmental quality is taken into consideration.

In addition, materialism may result in lower WTP values due to less concern about the effects of environmental damage on other people, ecosystem, and future generations. Materialism constitutes

a value orientation, which influences the environmentalism at a significant degree (Kidd and Lee 1997; Kilbourne and Pickett 2008). Hultman et al. (2015) developed a conceptual model to examine the environmental beliefs, attitudes toward ecotourism, behavioral intentions, and WTP in relation to the materialism and tourism motivation. A negative relation between materialism and WTP was detected. Moreover, a negative relation was identified between materialism and environmental beliefs. Finally, consumerism can also affect and shape the preferences of future generations. For instance, Yu et al. (2014) examined the WTP of citizens for purchase of "green food" in China. They found a positive relation between WTP and the frequency of shopping indicating that a potential increase of consumerism in the future could lead to higher WTP values.

According to Krysiak and Krysiak (2006), future preferences cannot be taken into consideration today due to the fact that the respective individuals are not yet in existence. As a result, the estimation of future preferences is characterized by a high degree of uncertainty.

3.2. Model Formation

As discussed in previous sections, the evolution of WTP values (i.e., the growth rate α) is influenced mainly by (a) the growth of income ("income growth factor"); (b) the depletion of environmental assets ("depletion factor"); (c) the elasticity of substitution between man-made and environmental goods and services ("substitution factor"); and (d) the changing preferences of future generations ("changing preferences factor"). However, in order to avoid "double-counting" issues, the substitution factor is omitted in the model developed, since:

- In case of perfect substitution between man-made and environmental assets, the effect of scarcity on WTP values is negligible and the non-market damages are estimated in consumption;
- In case of weak substitution, the effect on WTP values is captured via the depletion factor, as discussed below.

To consider the effect of income growth it is necessary to consider both the income elasticity of WTP and the growth rate of income, i.e.,

$$\alpha_{inc} = \omega \cdot g \tag{4}$$

where

g is growth rate of income expressed as percentage change from previous year.
ω is the income elasticity of WTP.

The environmental depletion (or scarcity) factor (α_{sc}) is given by:

$$\alpha_{sc} = \lambda \cdot q \tag{5}$$

where: q is the depletion rate on an annual basis and expressed as percentage decrease (or increase) from previous year.
λ is the "price" (i.e., WTP) elasticity of demand, estimated as follows:

$$\lambda = \frac{\partial WTP}{\partial Q} \frac{q}{WTP} \tag{6}$$

When a natural resource is depleted faster than it can be replenished, it is considered as non-renewable. In such cases, an alternative way to estimate the effect of scarcity over future WTP values is to make use of the "Hotelling's rule", which predicts that the shadow price of the stock of an exhaustible resource should grow at the rate of interest (Hotelling 1931).

Finally, preferences may evolve in the future and modify in an unknown way the attitude of future generations toward environmental assets. As mentioned, some of the factors associated with these changes are obvious, but others are unpredictable. Thus, it is not possible to foretell whether people

will care more about the environment in the future (i.e., green preferences) or less (i.e., materialistic preferences). Since future preferences are unknown, the preferences factor (α_{pr}) works at the proposed model as a "drift" (upwards or downwards) and is defined ad hoc.

Given that each and every of the above-mentioned factors has an independent and additive effect on the evolution of future WTP values, the total growth rate, α_{tot}, of WTP is given by:

$$\frac{\dot{WTP}}{WTP} = \omega\frac{\dot{Inc}}{Inc} + \lambda\frac{\dot{Q}}{Q} + \alpha_{pr} \tag{7}$$

When the right-hand expression is constant, the solution is $WTP_t = WTP_0 e^{\alpha t}$ with α given by the right-hand side:

$$\alpha_{tot} = \alpha_{inc} + \alpha_{sc} + \alpha_{pr} \tag{8}$$

where

α_{tot} is the total growth rate of WTP.
α_{inc} is the income growth factor.
α_{sc} is the environmental depletion (or scarcity) factor.
α_{pr} is the changing preferences factor.

The total growth rate, α_{tot}, is quite uncertain and its value can never be determined exactly. Therefore, simulation functions were constructed using flexible random walk-based stochastic models with and without drift (i.e., with and without change of preferences) to deal with the uncertainties involved. Random walk models are used in finance and economics in understanding and predicting the behavior of stock market prices, e.g., (Fama 1965; Smith 2002; Borges 2011), interest rates, e.g., (Pesando 1979; Newell and Pizer 2003; Bacchetta and van Wincoop 2007), growth and inequality, e.g., (Scalas 2006), etc. The random walk-based stochastic process is equivalent to a Brownian motion, and formally it is a Wiener process, named after Norbert Wiener's work in the early 1920s (Shafer and Vovk 2001). In general, a Brownian motion is any process S of the form:

$$S(t) = \mu t + \sigma W(t) \tag{9}$$

with $\mu \in R$ and $\sigma \geqq 0$.

Based on the general random walk model, the growth rate α in period (t) is estimated as follows:

$$\alpha_{tot}(t) = \theta(0) + kt + \varepsilon_t \tag{10}$$

where $\alpha_{tot}(t)$ is the total growth rate of WTP at time t.

$\theta(0)$ is the sum of $\alpha_{inc} + \alpha_{sc}$ at time 0.
k is the drift that reflects future preferences.
ε_t is a random component estimated by $\sigma W(t)$.

Since the growth rate of WTP is a continuous process dependent on its rate of change and time, it can be expressed as dependent on the differential change in the rate, i.e., it has to rewritten as a differential process:

$$d\alpha_{tot}(t) = kdt + \sigma dW(t) \tag{11}$$

Hence, $d\alpha_{tot}(t)$ is normally distributed with mean kt and standard deviation σ.

In order to implement the model, the following parameters should be empirically established:

- The income elasticity of WTP (ω)
- The income or growth rate (g) on an annual basis
- The WTP elasticity of demand (λ)

- The environmental depletion rate (q) on an annual basis
- The preferences factor (α_{pr}), which is expressed by k
- The volatility (σ) for the stochastic term

The elasticities ω and λ can be obtained from existing non-market valuation studies, while the preferences factor is defined ad hoc (i.e., it depends on the scenario set by the analyst). To facilitate this selection, it is suggested to express the evolution of preferences using the ratio WTP_T/WTP_{T0}, i.e., to make an arbitrary selection about the future WTP value (WTP_T). Having defined WTP_{T0} and WTP_T, the average preferences factor is estimated as follows:

$$k = \frac{1}{T - T_0} ln \frac{WTP_{T_0}}{WTP_T} \tag{12}$$

Similarly, in order to calculate the annual environmental depletion rate, q, the analyst may use the ratio $\Delta Q = Q_T/Q_{T0}$, which expresses the expected decrease (or increase) in the quality or quantity of the environmental good or service under investigation, according to the following equation:

$$q = \frac{1}{T - T_0} ln \frac{Q_{T_0}}{Q_T} \tag{13}$$

Finally, the volatility, σ, in similar models, is usually estimated using historical data series, e.g., (Newell and Pizer 2003). Nevertheless, in case of data unavailability, a different approach may be implemented by means of Monte Carlo simulation, as described in Section 4.

4. An Illustrative Example

4.1. Input Parameters

For illustrative purposes, we choose to estimate the effect of growth rate αtot between 2015 and 2050 to the WTP values of European temperate and boreal forests. To this end, the Ecosystem Service Value Database is used (van der Ploeg and de Groot 2010; de Groot et al. 2012). The original estimates of the database (Table 1) are converted into Euros in 2015 prices following Pattanayak et al. (2002) and using the purchasing power parity index (PPPI) and consumer price index (CPI) by the World Bank (2015) and OECD (2015). The mean, minimum and maximum values obtained by the database per ha and per year in Euros2015 are 922, 0.9 and 9345, respectively.

As regards the income elasticity of WTP, based on the results of the literature review discussed in Section 3.1, a central (i.e., likeliest) estimate of 0.7 was adopted. Moreover, for conducting sensitivity and probabilistic analyses the minimum and maximum values were taken equal to 0.1 and 1, correspondingly.

In order to estimate the annual growth rate, estimates from international organizations were taken into consideration, e.g., (OECD 2012a; PricewaterhouseCoopers 2015). For the purposes of our illustrative example, our model assumes an average rate of 2.0% per annum for European countries.

For the "environmental" elasticity of WTP, an average unitary elasticity (−1) was considered as the base value for the estimates according to empirical surveys (see Section 3.1). Furthermore, a minimum value of −2.3 and a maximum value of −0.5 were considered for sensitivity purposes.

The estimation of the environmental depletion rate was performed, taking into consideration the main findings from the study of OECD about the evolution of the biodiversity until 2050 (OECD 2012b). The projection for the case of the mature forests (primary forest) foresees a steady decrease until 2050 in all the examined regions within the framework of the baseline scenario. Specifically, the reduction of the primary forest area in OECD countries is expected to be approximately 14%.

Table 1. Monetary value of services provided by Temperate and Boreal Forests (in Int. $/ha/year-2007 values).

	No. of Estimates	Mean	Median	St.Dev.	Min	Max
Provisioning services	*9*	*671*	*450*	*867*	*121*	*1593*
1 Food	2	299	299	422	0	597
2 Water	3	191	121	123	118	333
3 Raw materials	4	181	31	322	2	662
4 Genetic resources						
5 Medicinal resources						
6 Ornamental resources						
Regulating services	*13*	*491*	*367*	*584*	*105*	*1212*
7 Air quality regulation						
8 Climate regulation	6	152	34	241	7	624
9 Disturbance moderation						
10 Regulation of water flows						
11 Waste treatment	3	7	0	13	0	22
12 Erosion prevention	1	5	5		5	5
13 Nutrient cycling	1	93	93		93	93
14 Pollination						
15 Biological control	2	235	235	330	1	469
Habitat services	*10*	*862*	*171*	*1342*	*51*	*3573*
16 Nursery service						
17 Genetic diversity	10	862	171	1342	51	3573
Cultural services	*26*	*990*	*139*	*2644*	*1*	*10028*
18 Esthetic information						
19 Recreation	25	989	138	2644	1	10027
20 Inspiration						
21 Spiritual experience						
22 Cognitive development	1	1	1		1	1
TOTAL	**58**	**3013**	**1127**	**5437**	**278**	**16406**

Source: de Groot et al. (2012).

Provided that future preferences are unknown, three different behavioral scenarios were examined, as follows:

- Scenario A: Unchanged preferences. In this case the ratio WTP_{2050}/WTP_{2015} equals to 1 and, consequently, the average (annual) preferences factor is zero.
- Scenario B: Green preferences. In this case the ratio WTP_{2050}/WTP_{2015} is assumed to be 2 and, consequently, the annual preferences factor is 1.98%.
- Scenario C: Materialistic preferences. In this case the ratio WTP_{2050}/WTP_{2015} is assumed to be 0.5 and, consequently, the annual preferences factor is −1.98%.

As mentioned, the volatility factor, σ, is a challenging issue contrary to the volatility of financial options, which is based on available historical information. In our case, the management assumption approach was employed (Mun 2006) using Monte Carlo simulations. In total, 1000 possible future growth rate α_{tot} values were estimated starting in 2015 and extending 35 years into the future, i.e., up to 2050. In order to represent the wider range of uncertainty that affects future growth rate, the Maximum Entropy theory was employed (Shannon 1948; Jaynes 1957; Gay and Estrada 2010). Since minimum, maximum, and mode values were known, the triangular distribution that maximizes the entropy was chosen (Harr 1987; Mishra 2002). Regarding environmental depletion, a uniform distribution was

adopted for the ratio $\Delta Q = Q_{2050}/Q_{2015}$ with min and max values equal to 70% and 110%, respectively. According to the analysis, the volatility σ was estimated at 20%.

4.2. Present Value of WTP Ignoring αtot

As a first step toward highlighting the effect of growth rate αtot on future WTP values, the present value (PV) of the recreational value of 1 ha of forestland for the period 2015–2050 is estimated. To this direction, the original (i.e., today's) value remains constant (i.e., the estimates are in constant prices) and equals to 922 $€_{2015}$. The PV of annual WTP recreational values per ha of forest land is estimated according to the following equation:

$$PV_{tot} = \sum_{t=0}^{35} \frac{WTP_t}{(1+s)^t} \tag{14}$$

where

PV_{tot} is the total present value of WTP for recreation per ha of forest land (i.e., 922 €2015).
WTP_t is the annual WTP for recreation per ha of forest land at time t.
s is the social discount rate.
t is the time in years.

An extensive discussion around the selection of the social discount rate is beyond the scope of this report. For illustrative purposes, a discount rate of 3.5% is adopted, as suggested by UK Treasury (H.M. Treasury 2003). Using the central estimate of 922 $€_{2015}$, the PV_{tot} for recreation per ha of forestland is estimated at19,360 $€_{2015}$.

Furthermore, in order to quantify variability due to the range of existing WTP estimates, a typical approach to probabilistic modeling, i.e., Monte Carlo simulation, is used. In this Monte Carlo simulation, a model is run repeatedly 1000 times, using WTP_{2015} as input parameter. The triangular probability distribution is constructed again according to the Maximum Entropy approach using likeliest, minimum, and maximum WTP values equal to 922, 0.9 and 9.45 $€_{2015}$ per ha and per year, respectively.

According to the probabilistic simulation, the mean PV of WTP, ignoring the growth rate α_{tot}, is approximately 72,200 $€_{2015}$, ranging between 1550 and 194,600 $€_{2015}$. Detailed results are presented in Tables 2 and 3.

Table 2. Monte Carlo simulation summary statistics for the PV of WTP.

Statistics	PV Ignoring α_{tot}	Scenario A	Scenario B	Scenario C
Mean	72,200	93,950	131,070	70,300
Median	64,480	85,850	116,020	64,120
St. Dev.	44,320	56,160	81,480	43,820
Minimum	1550	2440	5150	210
Maximum	194,610	278,180	392,360	209,340
Mean Std. Error	1400	1780	2580	1390

Table 3. Monte Carlo simulation percentiles for the PV of WTP.

Percentiles	PV Ignoring α_{tot}	Scenario A	Scenario B	Scenario C
100%	1550	2440	5150	210
90%	18,740	26,830	34,280	17,820
80%	29,950	41,610	54,290	28,830
70%	40,530	54,970	73,030	39,480
60%	52,470	69,840	93,270	52,120
50%	64,470	85,840	115,940	64,120
40%	78,710	101,450	142,830	76,170
30%	95,220	122,910	170,350	89,940
20%	113,400	144,690	205,080	107,210
10%	136,680	173,690	250,550	134,890
0%	194,610	278,180	392,360	209,340

4.3. Present Value of WTP Considering α_{tot}

4.3.1. Scenario A: Unchanged Preferences

According to Scenario A, the preferences remain unchanged during the time period considered. Nevertheless, WTP values are influenced by the growth of income and decrease in the area of primary forests. The former is captured in the model by α_{inc} and the latter is expressed by α_{sc}. In this particular Scenario, α_{pr} is zero. The values used in the base-case estimates are $\text{WTP}_{2015} = 922\,€$; $\alpha_{inc} = 1.40\%$ (which is estimated assuming an average growth rate of 2% per year and income elasticity of 0.7); and $\alpha_{sc} = 0.46\%$ (which is estimated assuming an average depletion rate of 0.46% per year and 'environmental' elasticity of WTP of −1).

Given that the model is based on a stochastic random walk process, 100 repetitions were made to estimate the mean PV. It is noted that in this case, contrary to the Monte Carlo simulation, the values of WTP, α_{inc} and α_{sc} remain constant. Thus, the results are only affected by the random component of the model, which is estimated by $\sigma W(t)$. Figure 1a illustrates 10 of the 100 random walks conducted during the modeling process for α_{tot} and Figure 1b illustrates the corresponding WTP values.

The mean random walk-based PV of WTP for the Scenario A is around 26,190 $€_{2015}$. The minimum and maximum PV of WTP estimates are 20,500 and 54,800 $€_{2015}$, respectively. In order to consider simultaneously the variability due to the range of WTP_{2015} estimates and the uncertainty related to α_{tot}, 1000 Monte Carlo simulations were run for WTP_{2015}, ω and λ. The results of the Monte Carlo simulation are presented in Tables 2 and 3.

In addition, a sensitivity analysis was carried out to explore the influence of input parameters on the PV of WTP. According to the sensitivity analysis, the most critical parameter is the WTP_{2015} value, followed by the ω.
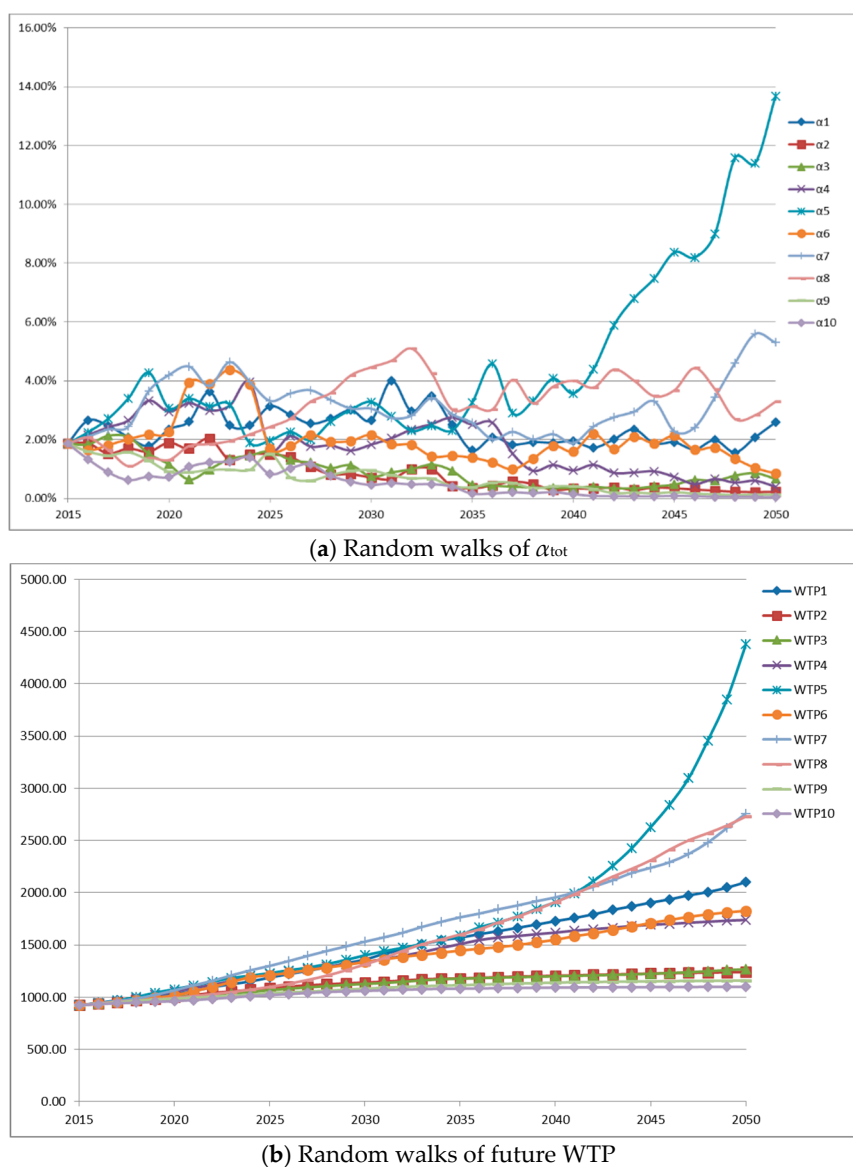
(**a**) Random walks of α_{tot}

(**b**) Random walks of future WTP

Figure 1. Ten random walks of α_{tot} (**a**) and of future WTP values (**b**) for Scenario A.

4.3.2. Scenario B: Green Preferences

According to Scenario B, the preferences become greener during the coming decades. Thus, WTP values are influenced by the growth of income, the decrease in the area of primary forests, and the green preferences of the individuals, which are captured in the model by α_{inc}, α_{sc} and α_{pr}. The values used in the base-case estimates are $WTP_{2015} = 922$ €; $\alpha_{inc} = 1.40\%$; $\alpha_{sc} = 0.46\%$; and $\alpha_{pr} = 1.98\%$ (this value is estimated assuming a ratio of WTP2050/WTP2015 equal to 2).

Similar to the process followed in the case of the Scenario A, 100 repetitions were made to estimate the mean PV, keeping the values of WTP, α_{inc}, α_{sc} and α_{pr} constant; thus, the estimates are only affected by the random component of the model. Figure 2a,b illustrate ten of the random walks for the α_{tot} and the corresponding WTP values for Scenario B, respectively.
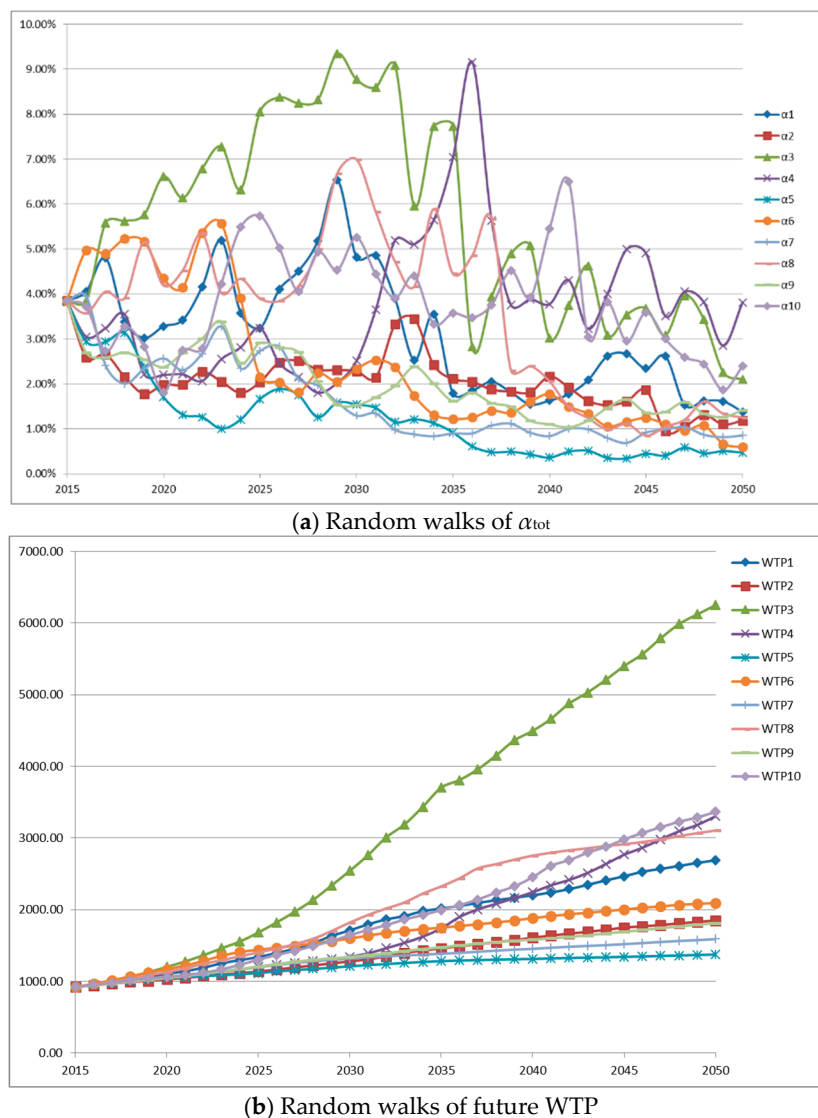
(**a**) Random walks of α_{tot}

(**b**) Random walks of future WTP

Figure 2. Ten random walks of α_{tot} (**a**) and of future WTP values (**b**) for Scenario B.

The mean PV of WTP for Scenario B, derived by the random walk model, is around 41,830 €$_{2015}$, and the minimum and maximum estimates are 22,700 and 230,300 €$_{2015}$, respectively. Again, Monte Carlo simulation was used to quantify the variability due to the range of exiting WTP estimates and the uncertainty related to α_{tot} model parameters, i.e., WTP$_{2015}$, ω, λ, and the WTP$_{2050}$/WTP$_{2015}$ ratio. The results of the Monte Carlo simulation are presented in Tables 2 and 3.

According to the sensitivity analysis results, the most critical parameter is the WTP$_{2015}$ value, followed by the WTP$_{2050}$/WTP$_{2015}$ ratio, and the ω.

4.3.3. Scenario C: Materialistic Preferences

According to Scenario C, society becomes more materialistic up to 2050. In this scenario, the values used in the base-case estimates are: WTP$_{2015}$ = 922 €; α_{inc} = 1.40%; α_{sc} = 0.46%; and α_{pr} = −1.98% (this value is estimated assuming ratio WTP2050/WTP2015 equal to 0.5).

Similarly to the process followed in the case of Scenarios A and B, the mean random walk-based PV of WTP for the Scenario C is around 19,050 Euros$_{2015}$, and the minimum and maximum estimates are 18,500 and 19,300 €$_{2015}$, respectively. Figure 3a presents ten random walks for α_{tot} and Figure 3b shows the corresponding WTP values for Scenario C.
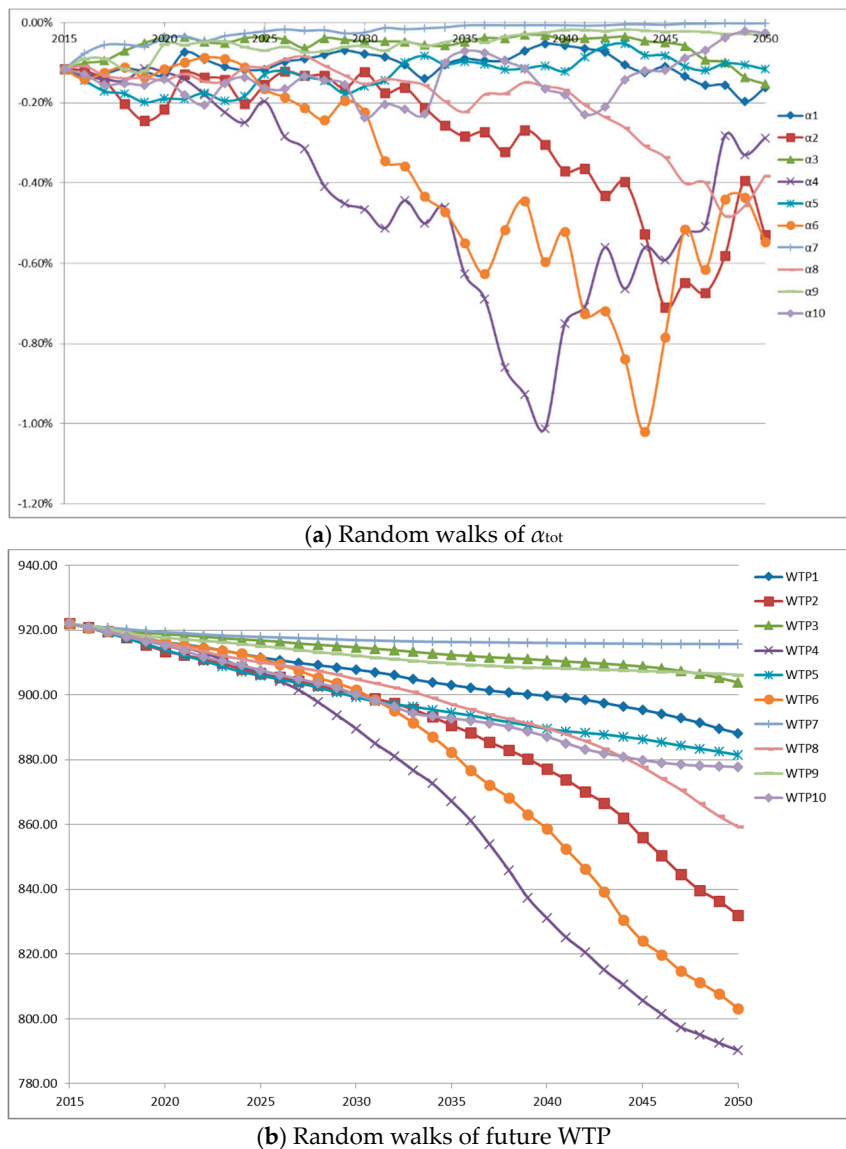
(**a**) Random walks of α_{tot}

(**b**) Random walks of future WTP

Figure 3. Ten random walks of α_{tot} (**a**) and of future WTP values (**b**) for Scenario C.

Monte Carlo simulations and sensitivity analyses were carried out to investigate the effect of WTP$_{2015}$, ω, λ, and WTP$_{2050}$/WTP$_{2015}$ ratio. Detailed results are illustrated in Tables 2 and 3. Similar to the sensitivity analysis results for Scenario B, the most critical parameter is the WTP$_{2015}$ value, followed by the WTP$_{2050}$/WTP$_{2015}$ ratio and the ω.

4.4. Discussion of Results

Tables 2 and 3 present results of the analysis with and without the effect of growth rate α_{tot}.

In all scenarios studied, the probabilistic assessment results in higher estimates than the deterministic analysis. The disparities between the deterministic estimates and the probabilistic simulations are attributed primarily to the wide range of WTP$_{2015}$ values, i.e., between 0.9 and 9345 €$_{2015}$ per ha/per year, which may be attributed to the preference uncertainty of the current generation.

The effect of total growth rate α_{tot} on the estimated PV of WTP is significant, even when preferences are assumed to remain constant. This is evident when comparing the results presented in Section 4.2 with those of obtained in Section 4.3.1 (i.e., the Scenario A). The mean (probabilistic) PV of WTP for Scenario A (i.e., 94,000 €2015) is 30% higher than the one estimated when ignoring the growth rate α_{to}t (i.e., around 72,200 €2015). The effect of total growth rate α_{tot} is even more apparent when changes in

the preferences of individuals are involved in the stochastic model. For instance, in the case of green preferences (i.e., Scenario B), the mean (probabilistic) PV of WTP is around 132,000 €$_{2015}$, which is almost twice the PV estimated when ignoring the growth rate α_{tot}.

The comparison of the estimates for the three Scenarios A, B, and C reveals the importance of considering the effect of evolving preferences, especially in long-term analyses. In fact, all other parameters being equal, the estimated PV of WTP is quite different for constant preferences, green preferences, and materialistic preferences. More specifically, the PV of WTP for the scenario of constant preferences (i.e., Scenario A) is about 35% higher than the estimated PV for the case of materialistic preferences (i.e., Scenario C), and about 30% lower than the PV estimated for the case of green preferences (i.e., Scenario B). More importantly, the comparison between the estimates of Scenarios B and C highlights the significance of the assumptions adopted regarding the evolution of preferences in the next decades. To wit, the PV estimated for Scenario B is around 85% higher than the corresponding value of Scenario C. This finding is worrisome considering future preferences are unknown. Therefore, potential behavioral patterns should be considered in climate change policy analyses, at least for sensitivity purposes.

5. Conclusions

Current methodological tools assume that there exists a perfect substitutability between market and non-market goods and that values related to environment remain unchanged. Consequently, in almost all IAMs assessments and "bottom-up" cost-benefit studies related to climate change policies, analysts take for granted that the preferences of current and future generations are fixed and given. However, this is far from the truth, especially when it comes to the valuation of environmental amenities. Ignoring changes in non-market values could (a) result in logical inconsistencies between the assumptions on future emissions and climate conditions, and the inputs of policy evaluation and optimization models; (b) lead to failure to recognize the influence of socioeconomic parameters in climate change policy; and finally (c) hinder the implementation of effective policies by distorting the damage assessment results. These issues are critical for accurate climate change economic assessments and timely policy responses.

As a first step toward handling the uncertainty in preferences with a focus on the value of non-market environmental goods and services, a robust methodology is proposed. More explicitly, a number of parameters, such as the growth of income, the depletion of environmental assets, the elasticity of income and demand, and the change in preferences towards the environment, are combined to a general random walk-based stochastic process that simulates uncertainty in the growth rate of the WTP values for environmental goods or services. By doing so, the model allows the analyst to visualize future paths of preference evolutions and to bring future values of damaged non-market assets realistically to the fore. For instance, the illustrative comparisons between Scenarios B and C show that—depending on the specific evolution of preferences—the resulting estimates may differ substantially (more than 80%). Thus, at least for sensitivity purposes, it is crucial to consider the change in behavioral patterns over time.

Nevertheless, much work needs to be done in future research. Embedding the model into Share Socioeconomic Pathways (SSPs) would add to the completeness and reliability of climate change economic assessments. This, of course, means that linkages between climate scenarios and the parameters of α should be created by developing separate modules in existing IAMs or other models, considering socioeconomic and environmental drivers of climate change. For instance, Drupp and Hänsel (2018) examined the effect of the scarcity of non-market on the economic appraisal of climate policy by calibrating DICE based on empirical evidence and performed a comprehensive analysis of the change in relative prices of non-market goods. They showed that neglecting relative prices changes leads to an underestimation of the social cost of carbon, in 2020, of more than 40%, which is equivalent to a decrease in pure time preference by more than a half percentage point. The proposed random-walk model of growth rate, α, could be also incorporated in modern valuation tools offering flexibility

in decision making, such as Real Options. Recently, Real Options analysis (ROA) is recognized as a promising approach for assessing climate change adaptation strategies, e.g., (H.M. Treasury 2009; World Bank 2009, 2011). The use of ROA, however, to appraise adaptation actions is so far limited, e.g., (Hertzler 2007; Woodward et al. 2011; Linquiti and Vonortas 2012; Kontogianni et al. 2013). In a more theoretical context, the social discount rate, say *s*, could be replaced by the "environmental" discount rate ($s - \alpha$) proposed by Fisher and Krutilla (1975). In fact, it is important to examine which existing discounting practices could implicitly cover some of the ground that the paper proposes, e.g., choosing discount parameters according to reasonable assumptions of increased scarcity of environmental assets, e.g., (Gollier and Weitzman 2010; Hoel and Sterner 2007; Traeger 2011). For example, Baumgärtner et al. (2015) using empirical data for ten ecosystem services across five countries, estimated the difference between the discount rates for ecosystem services and for manufactured consumption goods. They concluded that, on global average, ecosystem services should be discounted at a rate that is 0.9 ± 0.3%-points lower than the one for manufactured consumption goods. To the same direction, Gollier (2017) mentions that uncertainty related to the substitutability of ecosystem services in the future makes the investment in natural capital risky and tends to raise this discount rate. Yet, he concludes that this result is misleading because the uncertainty affects the growth rate of expected benefits, as well. The latter issue dominates the negative discounting effect, so that the economic value of natural capital is always increased. Finally, future work could also focus on refining the proposed model for market goods, as well. In this way, the model could be used in different application domains where it is required to explore possible futures.

The reliability of the model depends on the reliability of input data (elasticities of demand and income, projected growth rate of world economies, etc.), which means that the uncertainties do not vanish. But, to quote Keynes "it is better to be roughly right than precisely wrong".

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