Limits to substitution between ecosystem services and manufactured goods and intergenerational decision-making

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Abstract: This paper examines limits to substitution between ecosystem services and manufactured goods in consumer's utility and their implications for the economic evaluation of environmental policies. I provide a survey on current empirical evidence regarding substitution elasticities, which are ultimately limited by subsistence requirements in the consumption of ecosystem services. Subsequently, I extend the theory of 'ecological' or dual discounting by introducing such a subsistence requirement. I find that the 'relative price' of ecosystem services is non-constant and depends on the level of the consumption of ecosystem services over and above subsistence. The results suggests that the discount rate for ecosystem services should be, at present, about 1 to 5 percentage points lower compared to the rate for manufactured goods, and approach negative infinity as ecosystem services decline towards the subsistence level. This has important implications for the management of climate change and calls for safeguarding crucial ecosystem services.

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1 Introduction

I examine limits to substitution between consumption goods and ecosystem services and explore its implications for the economic evaluation of environmental policies.

Limited substitutability in both consumption and production is a core issue in the debate on sustainable development (Gerlagh and van der Zwaan 2002; Neumayer 2010). However, with the exception of substitutability between exhaustible resources and man-made capital, only very limited research exists that empirically estimates the elasticity of substitution for environmental goods in consumption and production (Dietz and Maddison 2009). This stands in contrast to theoretical work, where the issue of substitutability has recently resurfaced and gained attraction in two related fields of application: First, the dual discounting literature has respecified in bivariate models the long-known fact (Malinvaud 1953) that if utility depends on $n > 1$ goods that are less than perfect substitutes and have diverging growth rates there will be n good-specific discount rates, in particular an 'ecological' discount rate (Baumgärtner et al. 2014f; Gollier 2010; Gueant et al. 2012; Hoel and Sterner 2007; Traeger 2011; Weikard and Zhu 2005). Second, the debate stirred by the economic assessment of climate change in the Stern Review (2007) has triggered a rethinking of the correct specification of the damages function from climate change (Weitzman 2010). The latter relates in particular to the adverse impact of climate change on ecosystems and the respective repercussions for human well-being (Heal 2009a,b; Kopp et al. 2012; Neumayer 2007; Sterner and Persson 2008).

In this paper, I present the most comprehensive account on substitution elasticities between ecosystem services and manufactured goods to date. Besides discussing empirical evidence on substitutability in the standard constant-elasticity-of-substitution setting, I also consider a conceptual and theoretical extension. For this, I understand limits to substitution not only in terms of the current marginal rate of substitution of ecosystem services vis-a-vis manufactured consumption goods, but more specifically explore the implications for project evaluation of introducing an ultimate subsistence requirement in the consumption of ecosystem services. At the most basic level one may think of water, food and life-enabling ecosystem conditions.

My model set-up builds on the idea of capturing a very basal subsistence requirement through a survival threshold in an otherwise standard constant-elasticity-of-substitution utility function suggested by Heal (2009a,b), and its further formalization and generalization by Baumgärtner et al. (2014). Moreover, I draw on the analysis of dual discounting in a model with an aggregate manufactured- and an environmental good by Hoel and Sterner (2007) and Traeger (2011). I extend these 'ecological' or dual discounting models through introducing a subsistence requirement in the consumption of ecosystem services and analyse the properties of the resulting discount rates. I further illustrate the theoretical findings using empirically-founded yet hypothetical scenarios.

Overall, this paper makes several contributions for the economic evaluation and design of environmental policies. First, I find that the case for routinely including ecological discount rates in project evaluation is stronger than previously suggested: While Baumgärtner et al. (2014f) provide a conservative estimate of the dual discounting differential (or: 'relative price effect') of 1 percentage point, my scenario analysis suggests that this estimate should be adjusted by up to four times at present, and by substantially more for future periods if the consumption of ecosystem services is in decline and substitution possibilities are rather limited. Second, my analysis underlines the appropriateness of non-constant discount rates already in a deterministic setting: Depending on the growth rate of ecosystem services and the degree of substitutability, the good-specific discount rates may both decline or rise over time (cf. Trager 2011), and can additionally develop in opposite directions due to the subsistence requirement. Third, and more generally, the explicit considerations of a non-zero subsistence requirement has important implications for the management of many environmental problems, including climate change, and calls for securing the provisioning of crucial ecosystem services, as recently captured in the planetary boundaries idea of Rockström et al. (2009).

The paper is organized as follows: Section 2 surveys and discusses empirical evidence on substitution elasticities between ecosystem services and manufactured goods. Section 3 extends dual discounting models by including a subsistence requirement and illustrates the results using scenarios. Section 4 closes with a discussion and conclusion.

2 Ecosystem services and substitutability

2.1 Ecosystem services as contributors to well-being

As demonstrated by the Millennium Ecosystem Assessment (MEA 2005), human well-being fundamentally depends on the vitality of ecosystems and the ecosystem services (ES) they supply. ES provisioning opens up many basic opportunities which may be unattainable if the capacity of ecosystems to provide these services was diminished (e.g. Holland 2008). ES are broadly defined as the benefits humans derive from ecosystems and include a substantial variety of specific services. While *provisioning services*, including services related to food and fresh water, are regarded as the most direct inputs to well-being, a comprehensive set of services are necessary to satisfy human needs and wants. For example, without adequate *regulating services* such as climate- and flood regulation, personal safety and security from disasters may not be achievable.

While it is evident that ES are necessary constituents of human well-being (Dasgupta 2001), there is substantial uncertainty regarding the degree of their importance compared to manufactured goods and how their provisioning will evolve over time. The MEA (2005) analysis suggests that in the second half of the 20$^{\text{th}}$ century, 15 of the 24 ES categories they examined have deteriorated, while only four have improved. This assessment is far from being comprehensive, relies on various proxies or omits what is not readily measurable, and does not attempt an aggregation exercise to judge whether ES have deteriorated or increased on average. Baumgärtner et al. (2014f) attempt such an exercise by gathering proxies to account for a range of ES. Based on a simple calculation, they estimate that global ES have an average annual loss rate of 0.52% for the period 1950 to 2010 (ibid.: 23). The MEA (2005) further suggests that particularly two of the five key drivers of the loss of ES – climate change and excessive nutrient loading – will increasingly impact the change in ES. The IPCC (2007) provides a detailed account of how climate change might impact ES, causing i.a. a substantial extinction of species and widespread bleaching of corals even in the more optimistic scenarios. For increases in global mean temperature beyond those optimistic scenarios (i.e. a warming of greater than 1.5–2.5°C), the IPCC (2007: 48) projects that climate change along a business-as-usual path may lead to large-scale losses of ES, while the provisioning of ES may also decline independently of the climate change driver e.g. due to nutrient loading.

There are still many knowledge gaps regarding the contribution of ES to human well-being relative to manufactured goods and how much the past and projected loss of ES matters (e.g. Raudsepp-Hearne et al. 2010). For the current value-share of ES of overall consumption, there are a few indicative clues: For the lowest lower bound, one might take the value of food production, which was about 3% of global GDP in 2000 (MEA 2005: 6). However, the contribution of ES to human welfare is certainly greater: For example, the TEEB initiative (ten Brink 2011) has calculated that ES related to agriculture, forestry and fisheries contribute between 15-20% to an adjusted GDP in Brazil, India and Indonesia. This is close to evidence cited in Dasgupta (2010: 7), where the depreciation of forest, soil and fishery resources in Costa Rica amounted to about 10% of GDP. Nordhaus and Boyer (2000: 86) estimate that the capital value of climate-sensitive human settlements and natural ecosystems is 10% of GDP in the US, and assume it to be in the range from 5-25% for different aggregated world sub-regions. Overall this suggest that the current value-share of ES in overall global consumption may be somewhere between 3-25%, while it is more likely to be at the upper end due to incomplete data and imperfect valuation tools.

2.2 Substitutability between ecosystem services and manufactured goods

2.2.1 Conceptual considerations

A fundamental question in the debate on strong versus weak sustainability is whether substitution possibilities between ES/natural capital and manufactured goods/capital are limited or abundant (Gerlagh and van der Zwaan 2002; Neumayer 2010; Traeger 2011). Building on the seminal contributions by Dasgupta and Heal (1974), Solow (1974) and Stiglitz (1974), this discussion has been commonly set – both on the production as well as the consumption side – within a simple constant-elasticity-of-substitution (CES) framework and has focussed on determining the value of a single parameter: the CES.

However, the notion of the elasticity of substitution is much more general than being confined to a CES case. Since Hicks (1932[1963]) and Robinson (1933) have have introduced the basic definition, a rich literature has discussed many different elasticities of substitution, depending e.g. on the institutional setting or the number of goods considered.[1] It is well-known in this literature that neither the 'Hicksian' elasticity of substitution nor more elaborated versions need to be constant (e.g. Revankar 1971).

Studies that have discussed limits to substitution on a conceptual level – both in production and consumption – have concluded that while there may currently still exist ample substitution possibilities at the margin, "limits to substitutability in the medium term at least are real and important"; They further argue that these limits will be strictly binding in the long run due to thermodynamic limits in the production process or subsistence requirements in utility (Ayres 2007: 115; Ehrlich 1989; Heal 2009a,b; Stern 1997). That is: even though many parts of natural capital and ES are replaceable by technology, Fitter (2013) has argued that a number of supporting services (soil formation, water cycling etc.), selected final services (climate regulation) and goods (water supply, a safe and enjoyable environment) seem to be very hard if not impossible to substitute for with man-made devices (cf. Ayres 2007). Even if specific services were substitutable with technologies, human beings might still object to substitute them. I thus follow Traeger (2011) in assuming that the limited willingness to substitute in consumption is the ultimately relevant constraint.

An obstacle to advancing the discussion on limited substitutability is a lack of empirical evidence, which is – with the exception of substitutability between exhaustible energy resources and man-made capital – scarce to non-existent (Ayres 2007; Dietz and Maddison 2009; Neumayer 2010; Stern 1997).[2]

[1]See Bertoletti (2005), Frondel (2011) as well as Stern (2011) for useful overviews.

[2]A notable exception on the production side is Markandya and Pedroso-Galinato (2007).

2.2.2 Potential estimation routes for the elasticity of substitution

This section discusses different approaches that may be employed to elicit the elasticity of substitution between manufactured goods/income and ES.

While choice experiments seem to be a suitable approach, as they allow "to measure the individual's willingness to substitute one attribute for another" (Meyerhoff et al. 2009: 39), they have not yet been designed to yield an estimate of the elasticity of substitution (Meyerhoff 2013, personal communication). Furthermore, with the exception of Martini and Tiezzi (2013), which I address below, there is to my knowledge no revealed preference study from which an elasticity of substitution can be estimated.

Hanemann (1991) has shown that the WTA/WTP disparity can be explained with reference to limited substitutability: in a model with one environmental good and a composite manufactured good, the disparity will depend on the ratio of the income elasticity of demand for the environmental good to the Allen-Uzawa elasticity of substitution between the goods. As a result, for a given income elasticity of demand, a lower elasticity of substitution means a larger WTA/WTP disparity. It might therefore be possible to recover the elasticity of substitution indirectly from the experimental evidence. Shogren et al. (1994) and List (2004) have found some support for the substitutability hypothesis. However further work has shown that the disparity is – besides Hanemann's (1991) substitutability argument – driven i.a. by the endowment-, moral satisfaction- and learning effects as well as imprecise preferences (Morrison 1997a,b, 1998). Accordingly, it seems rather elusive to obtain a reliable estimate of the elasticity of substitution between manufactured goods and ES from the WTA/WTP disparity in particular because people will likely have imprecise preferences for those (public) ES of interest. Indeed, no study exists that properly disentangles these effects. This leaves one further estimation route which we will now cover in more depth.

2.2.3 Estimating the elasticity of substitution via the income elasticity of willingness-to-pay

A recently rediscovered way of indirectly inferring the (constant) elasticity of substitution of an ES makes use of its relation to the income elasticity of WTP (Baumgärtner et al. 2012, 2014f; Yu and Abler 2010). Based on previous results by Kovenock and Sadka (1981), Ebert (2003) has shown that for the case of the CES utility function[3], the income elasticity of WTP for an ES has an inverse relationship to the elasticity of substitution between a composite consumption good and the ES. More specifically, it follows from the standard utility maximization problem with a bivariate CES utility function (Baumgärtner et al. 2012, Appendix A.1)

$$U = \left[\alpha E^{\theta} + (1-\alpha)\, C^{\theta}\right]^{\frac{1}{\theta}} \quad \text{with } -\infty < \theta \leq +1;\; 0 < \alpha < 1,$$

that the income elasticity of WTP ξ is simply the inverse of the (constant) Hicksian elasticity of substitution σ (with $0 \leq \sigma < \infty$) and vice versa,

$$\frac{1}{\sigma} \;=\; 1-\theta \;=\; \xi$$

leading to the conclusion that

$$\text{if} \quad \xi \lesseqqgtr 1 \quad \text{then} \quad \sigma \gtreqqless 1$$

the income elasticity of WTP is smaller (greater) [equal to] unity if the ES and consumption goods are substitutes (complements) [Cobb-Douglas].

Due to this relationship, the elasticity of substitution between manufactured goods and ES can be estimated indirectly based on data from a range of valuation studies that estimate a constant[4] income elasticity of WTP, calculated as point-elasticities evaluated

[3]This implies that both goods are 'normal', which is not the case for every single ES. McFadden and Leonard (1993) e.g. find negative income elasticities for specific ES (Horowitz and McConnell 2003).

[4]Note that income elasticities are generally not constant but may vary across individuals and also across aggregate measures, as e.g. found in Ready et al. (2002). Broberg (2010), however, finds that a model with a constant income elasticity does not produce a worse overall fit than those where the income elasticity of WTP is a (non-)linear function.

at the mean values of the income variables. These estimates have been reported in numerous 'contingent' valuation (CV) studies,[5] where the mean income elasticity of WTP for ES ξ is found to be in the range from 0.1 to 0.6, implying values of the CES-substitutability parameter θ of 0.4 to 0.9 and mean elasticities of substitution in the range 1.67 to 10 (see Table 1 for an overview of selected studies).

This clear result of income elasticities smaller than unity obtained throughout the CV literature has been challenged by Schläpfer (2006, 2008, 2009), Schläpfer et al. (2008), and Schläpfer (2011a,b). Schläpfer argues that the small income elasticities may be an artefact of the current design of CV studies, suffering from anchoring effects, updating and strategic behaviour, which may lower the income effect. He compares CV with voting-based studies (Schläpfer and Hanley (2003, 2006), Schläpfer and Witzig (2006), Schläpfer et al. (2008) and Schläpfer (2011a,b) and finds support for an income elasticity of WTP for public ES equal to or greater than unity. The only revealed preference study that estimates an income elasticity of WTP (Martini and Tiezzi 2013) implies an elasticity of substitution of about unity. Further work on the robustness of income elasticities derived from stated and revealed preference methods is therefore necessary.

The currently best available estimate for a composite ES at the global level comes from a meta-study on income effects in valuation studies by Jacobsen and Hanley (2009), who gather 145 different WTP estimates from 46 CV studies across six continents. They find, averaging over the very different biodiversity-related ES (i.e. assuming that they are part of a homogeneous good), that the income elasticity of the WTP for ES is 0.38 ± 0.14, implying an elasticity of substitution vis-a-vis income or aggregate manufactured goods of 2.63 [1.92 to 4.17] and a CES-substitutability parameter of 0.62 [0.48 to 0.76].

Two shortcomings of the study suggest caution in using this result as an estimate of the elasticity of substitution for an aggregate global ES e.g. for integrated assessment modeling: First, there is a non-representative study selection due to limited data

[5] See, e.g., Broberg (2010), Carlsson and Johansson-Stenman (2000), Chiabai et al. (2011), Hammitt et al. (2001), Hœkby and Sœderqvist (2003), Khan (2009), Kristrœm and Riera (1996), Liu and Stern (2008), Ready et al. (2002), Sœderqvist and Scharin (2000), Wang and Whittington (2000), Wang et al. (2013), as well as Yu and Abler (2010).

Table 1: Estimates of the elasticity of substitution between manufactured consumption goods and ecosystem services

Study	Point estimate	Sensitivity/ Error range	Environmental service	Location
Selected estimates derived from the income elasticity of WTP				
Broberg (2010)	2.69	2.12 – 3.66	Existence of predator species	Sweden
Carlsson/Johansson-Stenman (2000)	3.13	–	Air quality improvement	Sweden
Jacobsen/Hanley (2009)	2.63	1.92 – 4.17	Aggregate biodiversity	Global
Martini/Tiezzi (2013)	0.86	0.71 – 1.09	Air quality improvement	Italy
Schläpfer/Hanley (2003)	1<	–	Landscape amenities	Switzerland
Wang/Whittington (2000)	3.70	3.17 – 11.30	Air quality improvement	Bulgaria
Wang et al. (2013)	4.76	3.85 – 6.25	Water quality improvement	China
Whitehead et al. (2000)	4.18	2.38 – 17.24	Recreation improvements	USA
Yu/Abler (2010)	4.95	3.17 – 11.30	Air quality improvement	China
Estimates used in applied modeling				
Hoel/Sterner (2007)	0.5	0.5 – 1	Aggregate	Global
Sterner/Persson (2008)	0.5	≥ 1	Aggregate	Global
Kopp et al. (2012)	0.75	0.5 – 1	Aggregate	Global
Gollier (2010)	1	0.5 – 1.5	Aggregate	Global

availability, with studies from developed countries being over-represented, and second a non-representative object selection, with more complex ES not being represented since no valuation studies exist to capture their values. I hypothesize that these two biases are more likely than not to lead to an underestimation of the income elasticity, translating into an overestimation of the elasticity of substitution. This may be because more complex ES may have a more complementary relationship with manufactured goods, and households in developing countries may more directly rely on ES for their subsistence.

2.2.4 Empirical estimates in perspective

This section showed that the only approach that currently yields useful empirical estimates of the elasticity of substitution between ES and manufactured goods is an indirect route via the income elasticity of WTP. These indirect estimates suggest that the elasticity of substitution is currently substantially larger than one, thus indicating a substitutive relationship between ES and income/manufactured goods. However, almost all of these valuation studies solely capture partial elasticities with respect to a specific ES, while the meta-study of Jacobsen and Hanley (2009) represents an imperfect approximation as argued above.

It is an interesting questions why almost all valuation studies indirectly imply that elasticities of substitution are greater than unity. This may reflect the fact that the subject of these studies are generally ES with locally restricted benefits, such as aesthetic or recreational values, or that people are still willing to substitute ES for manufactured goods at the current provisioning level, which may be far away from absolutely binding subsistence requirements. More generally, it may be questioned whether these stated preference methods capture the precise actual and relevant preferences (cf. the critiques by Morrison and Schläpfer), or whether preferences are stable in the first place (Stern 1997). To shed light on these considerations, one would need to perform long-term panel data studies that scrutinize how the elasticity of substitution (or indirect estimates of it) develops over time and by what it is influenced.

Another central question derives from examining the evidence base as assembled in Table 1 that contrasts estimates of the elasticity of substitution derived from empirical work and parameter values used in applied modelling. It is particularly noteworthy that while (almost) all empirical studies point to an elasticity greater than unity, (almost) all applied modelling studies have chosen elasticities of substitution smaller than unity for their analysis. This finding may simply be due to the fact that none of these modelling studies seem to have examined empirical evidence upon which to base their parametrization.[6] However, I hypothesize that the applied modelling studies would not

[6] This impression is based on the papers of and exchange with Gollier, Persson and Sterner.

have settled with the empirical estimates as presented in Table 1 (yet potentially more carefully considered them in their analyses) due to the widely held belief that substitution possibilities are more limited at the macro- than at the micro level (Stern 1997). On this note, it is worth quoting Sterner and Persson (2008: 71) at length:

> *"[If] there is a range of [ES] with different elasticities of substitution, then the relevant aggregate number is very likely not going to be the average of those elasticities. It is the goods [...] with low elasticities that will dominate the calculation, since these will be the ones with increasing shares in utility. This goes for clean water, pollination services, and many other subtle aspects of the ecosystem that we take for granted as long as they are plentiful."*

This criticism concerning a likely mis-aggregation of (easier) available estimates of substitutability and the importance of indispensable ES that will ultimately dominate the overall elasticity of substitution of a composite ES seems compelling (cf. Section 2.2.2). Yet, I hypothesize that the correct value of the current elasticity of substitution lies between the potentially inflated indirect estimate derived from the data of Jacobsen and Hanley (2009) and the low value as considered by Sterner and Persson (2008).

Indeed, the need to reconcile the fact that mankind ultimately cannot survive without the provisioning of basic ES and the empirical evidence suggesting that the current willingness to substitute ES for manufactured goods is still relatively high leads to an important insight: The elasticity of substitution is non-constant (Heal 2009a,b; Baumgärtner et al. 2014). One plausible hypothesis based on the analysis of Baumgärtner et al. (2014) is that the elasticity of substitution varies with the availability of ES in relation to the services necessary to meet basic subsistence requirements. Specifically, humans will not be willing to substitute ES for manufactured goods if these subsistence requirements are not sufficiently met and will be willing to substitute freely when ES are available in abundance (see Figure 1). This implies that even if the aggregate ES is initially considered as a substitute ($\sigma > 1$), it will eventually become a complement due to the subsistence requirement. This motivates exploring the implications of subsistence requirements not only in a static (cf. Baumgärtner et al. 2014) but also in an intertemporal context.

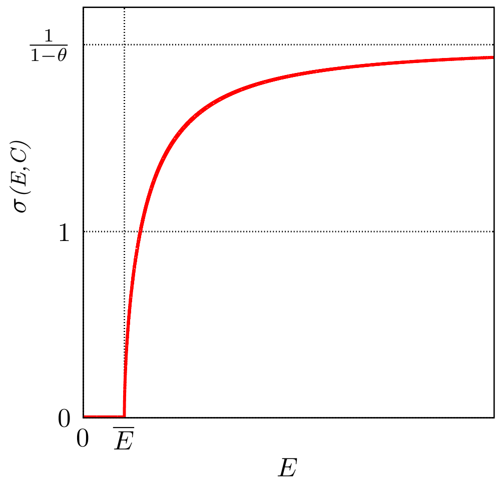

Figure 1: Elasticity of substitution $\sigma(E, C)$ as a function of the consumption of ecosystem services for utility function U_h from Equation (2) below, for a fixed $C > 0$ with $\theta = 0.5$. Adapted from Baumgärtner et al. (2014: 8).

3 Dual discounting under a subsistence requirement

The economic study of subsistence requirements has a rich history, encompassing seminal contributions by Klein and Rubin (1947-48), Samuelson (1947-48) as well as Geary (1949-50) and Stone (1954). More recently, the consideration of subsistence requirements has been shown to be of relevance in a range of fields, including growth, development and environmental economics (e.g. Atkeson and Ogaki 1996; Easterly 1994; King and Rebelo 1993; Kraay and Raddatz 2007; Ravn et al. 2008; Steger 2000; Strulik 2010).[7] Most of these studies consider a subsistence threshold in univariate utility functions, however Pezzey and Anderies (2003) and Heal (2009a,b) consider cases where utility depends not only on manufactured goods but also on some form of ES, which is subject to a subsistence requirement. Pezzey and Anderies (2003) conceptualize subsistence in terms of minimum nutrition levels, whereas Heal (2009a: 279) notes more comprehensively that "[t]here is a minimum level of [ES] needed for survival—think of this as water,

[7]While I focus on subsistence in consumption, it should be noted that the equivalent on the production side, 'critical natural capital' (Brand 2009; Ekins 2003), is a key idea in environmental economics.

air, and basic foodstuffs". Other discussants refer to "essential lifeservices" provided by ecosystems (Traeger 2011: 217) or remark that "a large part of what the natural environment offers us is a necessity" (Dasgupta 2001: 125).

While there is no generally accepted notion of subsistence (Steger 2000), Sharif (1986: 555) argues that it must go beyond a mere consideration of basic physical needs to encompass the "needs [concerning] physical and mental survival". Along these lines, a subsistence requirement concerning ES would not only include food, water, bodily security and more broadly life-enabling ecosystem conditions (see Wallace (2007) for an overview), but potentially also cultural ES like the experience of 'naturalness' or the existence of sacred natural environments. Relatedly, Baumgärtner et al. (2014: 2) define a subsistence requirement more generally to "encompass a homogeneous composite good to which an individual attaches absolute priority before considering trade-offs with other goods". Other discussants use the terminology of basic needs (Rauschmayer et al. 2011) in closer relation to the earlier discourse on sustainable development (WCED 1987), which usually concerns a more extensive coverage of required goods and services.

As a working hypothesis, I will adopt the narrower definition of subsistence requirements in terms of a survival threshold (cf. Heal 2009a,b), which includes essential services related to the consumption of water, food as well as life-enabling ecosystem conditions.

3.1 Model and definitions

This section develops a dual discounting model that considers a subsistence threshold in the consumption of ES:

There are two composite goods, a manufactured good C and an ecosystem service E, of which an amount $\overline{E}$ is needed to satisfy the subsistence needs of a representative agent. Her preferences are represented by a utility function

$$U(E,C) = \begin{cases} U_l(E) & \text{for } E \leq \overline{E} \\ U_h(E,C) & \text{else} \end{cases} \tag{1}$$

where $U_h(\cdot,\cdot)$ is a twice continuously differentiable function which is strictly monotonic in both arguments and strictly quasi-concave (cf. Baumgärtner et al. 2014).

In line with the conception of subsistence as a sharp survival threshold, capturing the consumption of essential ES, we only consider utility in the domain where the subsistence requirement is met, i.e. $E > \overline{E}$. As a suitable specification for $U_h(\cdot,\cdot)$, I follow Heal (2009a,b) and Baumgärtner et al. (2014), and use a generalized modification of the Stone-Geary and the constant elasticity of substitution (CES) functions:

$$U_h(E,C) = \left[\alpha\left(E-\overline{E}\right)^{\theta} + (1-\alpha)\,C^{\theta}\right]^{1/\theta} \quad \text{with} \quad -\infty < \theta \leq +1;\ 0 < \alpha < 1, \tag{2}$$

where θ is the usual CES-substitutability parameter.

My modelling set-up extends the CES-CIES approaches of Gueant et al. (2012), Hoel and Sterner (2007) and Traeger (2011): A representative, (potentially) infinitely lived agent has perfect knowledge about the future[8] and maximizes an intertemporal discounted-utilitarian, constant intertemporal elasticity of substitution (CIES) social welfare function based on the instantaneous utility function U_h (from Equation 2). Welfare is given by

$$W = \int_0^T \underbrace{\underbrace{\frac{1}{1-\eta}\left[\alpha(E_t-\overline{E})^{\theta} + (1-\alpha)C_t^{\theta}\right]^{\frac{1-\eta}{\theta}}}_{u(E,C)}\ e^{-\delta t}}_{U(E,C,t)}\,dt, \tag{3}$$

where δ is the utility discount rate and η is the inverse of the CIES with respect to the within-period aggregate consumption bundle $\widetilde{C} = \left[\alpha(E_t-\overline{E})^{\theta} + (1-\alpha)C_t^{\theta}\right]^{\frac{1}{\theta}}$. In contrast to previous studies, we assume a finite time horizon T, as intertemporal welfare would otherwise be undefined for $E_t < \overline{E}$.

Following Traeger (2011: 216), I define social *discount factors* and *-rates* as follows: The good-specific *discount factors* for good x_i, with $x_i, x_j \in \{E_t, C_t\}$ and $i \neq j$, relating the additional value of good x_i between the points in time t and t_0 for a given, but not necessarily optimal, consumption path of E and C are

$$P_i(t,t_0) = \frac{\frac{\partial U(E_t,C_t,t)}{\partial x_i}}{\frac{\partial U(E_t,C_t,t_0)}{\partial x_i}}. \tag{4}$$

[8]See Gollier (2010) for a treatment of the case of risk.

The corresponding good-specific *discount rates* for good i are given by:

$$\rho_i(t) = -\frac{\frac{\partial^2 U}{\partial t \partial x_i}(t) + \frac{\partial^2 U}{\partial^2 x_i}(t)\dot{x}_i(t) + \frac{\partial^2 U}{\partial x_j \partial x_i}(t)\dot{x}_j(t)}{\frac{\partial U}{\partial x_i}(t)}. \tag{5}$$

Using $U(E, C, t)$ from Equation (3), this can be expressed in simpler terms as (cf. Heal 2005, 2009 Eq. 2; Baumgärtner et al. 2014f):

$$\rho_E(t) = \delta + \psi_{EE} g_E + \psi_{EC} g_C \tag{6}$$

and

$$\rho_C(t) = \delta + \psi_{CC} g_C + \psi_{CE} g_E, \tag{7}$$

where ψ_{EE} (resp. ψ_{CC}) is the elasticity of marginal utility of consumption of the aggregate ES (resp. manufactured good) with respect to the ES (manufactured good), and $\psi_{EC}(\psi_{CE})$ is the elasticity of marginal utility of consumption of the ES (manufactured good) with respect to the manufactured good (ES); The growth rates g_i are defined as $g_i(t) = \frac{\dot{x}_i(t)}{x_i(t)}$, while I omit the time subscript for the growth rates in the following and will often assume them to be constant.

3.2 Results and illustrations

We now derive and analyse the good-specific discount rates in the presence of a subsistence requirement in the consumption of an ES.

The discount rate for the ES is given by (see Appendix A.1):[9]

$$\rho_E(t) = \delta + \frac{E_t}{E_t - \overline{E}} \frac{\alpha\eta(E_t - \overline{E})^\theta + (1-\alpha)(1-\theta)C_t^\theta}{\alpha(E_t - \overline{E})^\theta + (1-\alpha)C_t^\theta} g_E + \frac{(1-\alpha)C_t^\theta(\eta - (1-\theta))}{\alpha(E_t - \overline{E})^\theta + (1-\alpha)C_t^\theta} g_C \tag{8}$$

while the manufactured good discount rates is given by

$$\rho_C(t) = \delta + \frac{\alpha(1-\theta)(E_t - \overline{E})^\theta + (1-\alpha)\eta C_t^\theta}{\alpha(E_t - \overline{E})^\theta + (1-\alpha)C_t^\theta} g_C + \frac{\alpha E_t (E_t - \overline{E})^{\theta-1}(\eta - (1-\theta))}{\alpha(E_t - \overline{E})^\theta + (1-\alpha)C_t^\theta} g_E\,. \tag{9}$$

[9] Note that what Hoel and Sterner (2007: 272) call the "combined effect of discounting [they only explicitly calculate the discount rate for manufactured goods ρ_C^{CES}] and relative price increase of environmental goods", denoted by R, is simply the discount rate for ES ρ_E^{CES} in a CES setting. What they term the 'relative price effect' is the difference in good-specific discount rates $\Delta\rho^{CES}$.

Following Traeger (2011), we can rewrite these to obtain the overall growth- and real substitution effects

$$\rho_E(t) = \delta \underbrace{+\eta \left[\frac{\alpha E_t(E_t - \overline{E})^{\theta-1} g_E + (1-\alpha) C_t^\theta g_C}{\alpha(E_t - \overline{E})^\theta + (1-\alpha)C_t^\theta}\right]}_{\text{overall growth effect}} \underbrace{-(1-\theta)(1-\alpha)C_t^\theta \left[\frac{g_C - \frac{E_t}{E_t - \overline{E}} g_E}{\alpha(E_t - \overline{E})^\theta + (1-\alpha)C_t^\theta}\right]}_{\text{real substitution effect}} \tag{10}$$

and

$$\rho_C(t) = \delta \underbrace{+\eta \left[\frac{\alpha E_t(E_t - \overline{E})^{\theta-1} g_E + (1-\alpha) C_t^\theta g_C}{\alpha(E_t - \overline{E})^\theta + (1-\alpha)C_t^\theta}\right]}_{\text{overall growth effect}} \underbrace{+(1-\theta)\alpha(E_t - \overline{E})^\theta \left[\frac{g_C - \frac{E_t}{E_t - \overline{E}} g_E}{\alpha(E_t - \overline{E})^\theta + (1-\alpha)C_t^\theta}\right]}_{\text{real substitution effect}} . \tag{11}$$

Using these, it is straightforward to derive the difference in the good-specific discount rates, also termed 'relative price effect' by Hoel and Sterner (2007):

$$\Delta\rho(t) = \rho_C(t) - \rho_E(t) = (1-\theta)\left[g_C - \frac{E_t}{E_t - \overline{E}} g_E\right] . \tag{12}$$

For the special case of $\overline{E} = 0$, $\Delta\rho$ collapses to the standard formula $\Delta\rho^{CES} = (1-\theta) \times [g_C - g_E]$ as presented in Traeger (2011).

For $\overline{E} > 0$, the representative agent is concerned with the growth rate of the ES over and above the subsistence requirement, which gives rise to the correction factor $\frac{E_t}{E_t - \overline{E}}$ that depends on the distance of the level of the ES to the subsistence threshold. This implies that given the CES-substitutability parameter and provided that both growth rates are constant but unequal, a non-constant 'relative price effect' will emerge that depends on how much of the environmental good is still available in relation to the subsistence level. Interestingly, the non-constant elasticity of substitution σ in the presence of the subsistence threshold, derived in Baumgärtner et al. (2014), plays no direct role for the determination of the 'relative price effect'.

We now examine the good-specific discount rates and their difference in more detail:

Proposition 1

For $E_t > \overline{E}$, the 'relative price effect' has the following properties:

- For $E_t \rightarrow \overline{E}$ (which implies $g_E < 0$), it follows from Equation (12) that the difference in the good-specific discount rates goes to infinity ($\Delta\rho \rightarrow \infty$).

- If $g_C > 0 > g_E$, the existence of a positive subsistence threshold increases the difference in the good-specific discount rates $\Delta\rho$; if instead $g_C > g_E > 0$, it decreases $\Delta\rho$. If $g_E = 0$, the subsistence threshold is obviously irrelevant.

Proof. Clear. □

Instead of a formal analysis of the long-run schedules of the good-specific discount rates, I perform an illustration-based examination. The reason is that such an analysis would be very similar to Traeger's (2011), except that in the case of a constant negative growth rate of ES ($g_E < 0$) the consumption of ES will approach the subsistence requirement $\overline{E}$ and the ES components will dominate the discount rates.

To illustrate the time profile of the dual discount rates, I compare the modified discounting formulas in the presence of a subsistence threshold (ρ_E and ρ_C) with the standard CES case (ρ_E^{CES} and ρ_C^{CES}) by using four examples for a time horizon of approximately 300 years. We first consider the parameter specifications as used for Figure 1 of Hoel and Sterner (2007: 275) to facilitate comparison.

Example 1. Let $\delta = 1\%$, $\eta = 1.5$, $\theta = -1$, $\alpha = 0.1$, $E_0 = C_0 = 1$, $g_C = 2.5\%$ and $g_E = 0\%$. We further add a subsistence requirement of $\overline{E} = 0.15$.

Figure 2 illustrates Example 1 and depicts the time development of the discount rate for the manufactured good and the ES. It shows that the manufactured good discount rate schedules for the standard CES case (red line) and with a subsistence requirement (blue) have almost identical development paths, are always higher than the constant single good case (black), rise over time and approach the same steady state value of 6%. The discount rates for the ES (green, purple) have parallel schedules so that the 'relative price effect' is always constant at $\Delta\rho = \Delta\rho^{CES} = 5\%$.

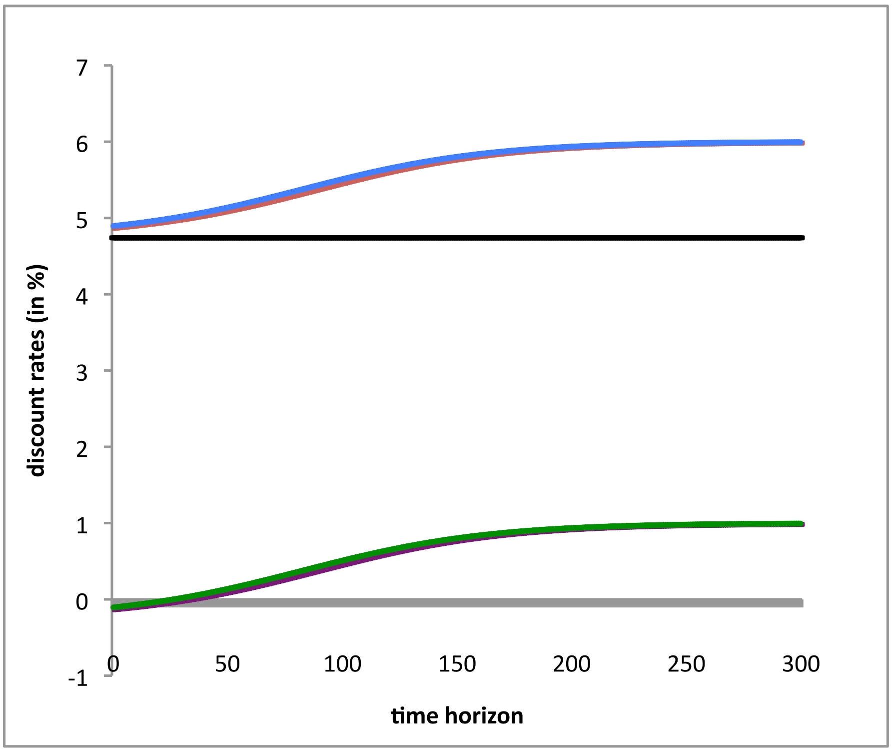

Figure 2: Illustration of **Example 1**: The red (blue) line shows the time development of the manufactured good discount rate ρ_C^{CES} (ρ_C) for the CES case (with a subsistence threshold). The black line represents the single manufactured good case of $\rho = \delta + \eta g_C$. The purple (green) line depicts the corresponding discount rate for ES ρ_E^{CES} (ρ_E).

Next, I change the crucial parameter values for θ and the growth rates g_C and g_E to those used in the empirical analysis on dual discounting by Baumgärtner et al. (2014f). This simulation – as in Hoel and Sterner (2007) and Traeger (2011) – carries the assumption that the growth rates of the past 50 years will hypothetically remain unchanged for the relevant time horizon as no mechanism for an optimal management of the manufactured good as well as the ES is specified.

Example 2. Let $\delta = 1\%$, $\eta = 1.5$, $\theta = 0.62$ (from Baumgärtner et al. (2012, 2014f) based on Jacobsen and Hanley (2009)), $\alpha = 0.1$, $E_0 - \overline{E} = C_0 = 1$, with $\overline{E} = 0.15$, and $g_C = 1.88\%$, $g_E = -0.52\%$ (both from Baumgärtner et al. 2014f).

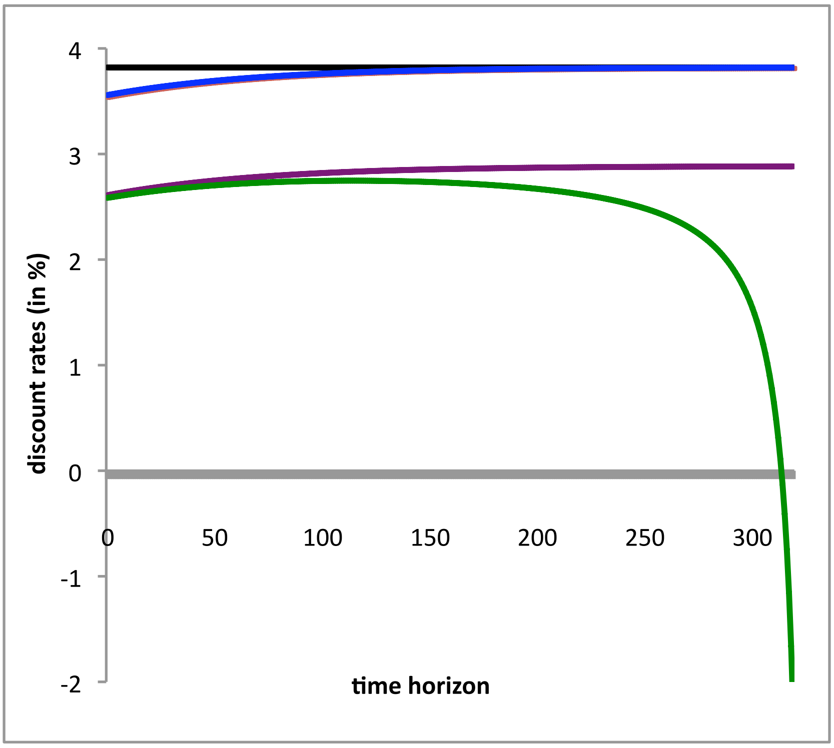

Figure 3: Illustration of **Example 2**: Description as in Figure 2.

Figure 3 illustrates Example 2: The manufactured good discount rate schedules for the standard CES case (red line) and with subsistence requirements (blue) both quickly approach the constant single good discount rate (black) of 3.82%. For the ES discount rate, we observe a stark difference between the the CES case (purple) and the one with a subsistence requirement (green): While the ES discount rate in the CES case increases over time and approaches a steady state value of approximately 2.88%, the ES discount rate in the presence of a subsistence threshold is always lower, first slightly increases due to the overall growth effect, and finally decreases and approaches minus infinity as the consumption of ES approaches the subsistence level (after 326 years). In line with Baumgärtner et al. (2014f), the 'relative price effect' remains at about 1% percentage point for a 200 year time horizon. As noted above, such a case of a constant negative growth rate of ES would certainly not be optimal under active ES management.

I now change the crucial CES-substitutability parameter θ to capture scenarios of limited substitutability:

Example 3. Let $\delta = 1\%$, $\eta = 1.5$, $\theta = -1$ (cf. Hoel and Sterner 2007; Sterner and Persson 2008), $\alpha = 0.1$, $E_0 = C_0 = 1$, with $\overline{E} = 0.15$, $g_C = 1.8\%$ and $g_E = -0.52\%$.

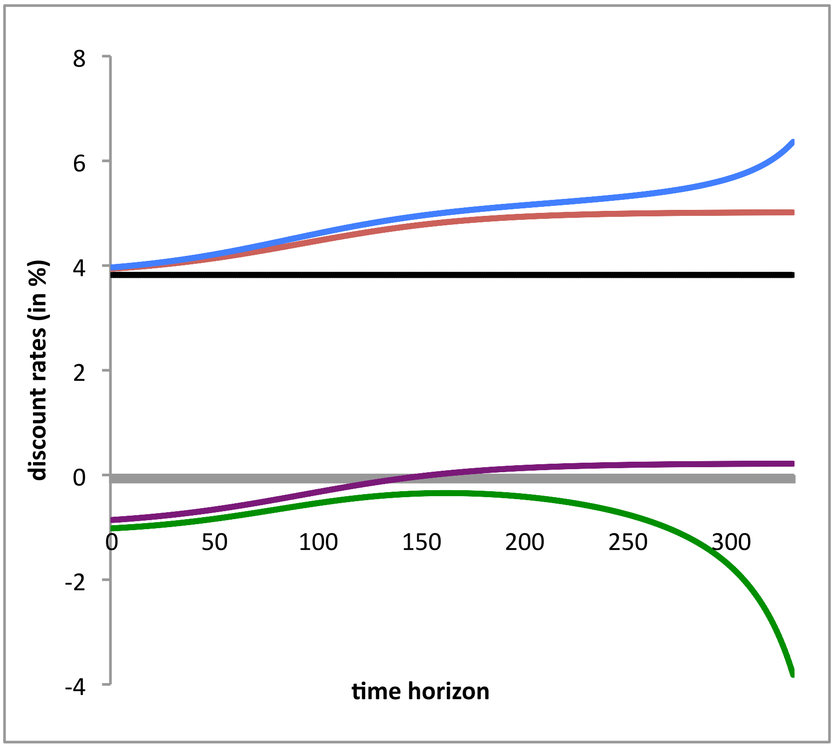

Figure 4: Illustration of **Example 3**. Description as in Figure 2.

Figure 4 depicts again the time development of the five discount rates. Initially, we now have a 'relative price effect' of approximately 4.8%. The analysis of the CES case (cf. Traeger 2011: 219) shows that for $\theta < 0$ and $\eta < (1 - \theta)$, the discount rates of both manufactured goods and ES (red, purple) grow over time. In contrast, the good-specific discount rates under the subsistence requirement develop in opposite directions: While the discount rate for manufactured goods (blue) increases to infinity as the consumption of ES approaches the subsistence threshold ($E_t \to \overline{E}$), the discount rate for ES (green) declines towards negative infinity, as in Example 2.

Lastly, I use parameter values that I hypothesize to be the best approximation based on the discussion in Section 2. I keep Baumgärtner et al.'s (2014f) estimate of the growth rates but follow the argument that the current best estimate of θ lies between Sterner and Persson's (2008) value of -1 and the indirect estimate of 0.62 based on Jacobsen and Hanley (2009). We thus consider $\theta = -0.333$, as used in Kopp et al. (2012):

Example 4. Let $\delta = 1\%$, $\eta = 1.5$, $\theta = -0.333$ (cf. Kopp et al. 2012), $\alpha = 0.1$, $E_0 = C_0 = 1$, with $\overline{E} = 0.15$, $g_C = 1.8\%$ and $g_E = -0.52\%$.

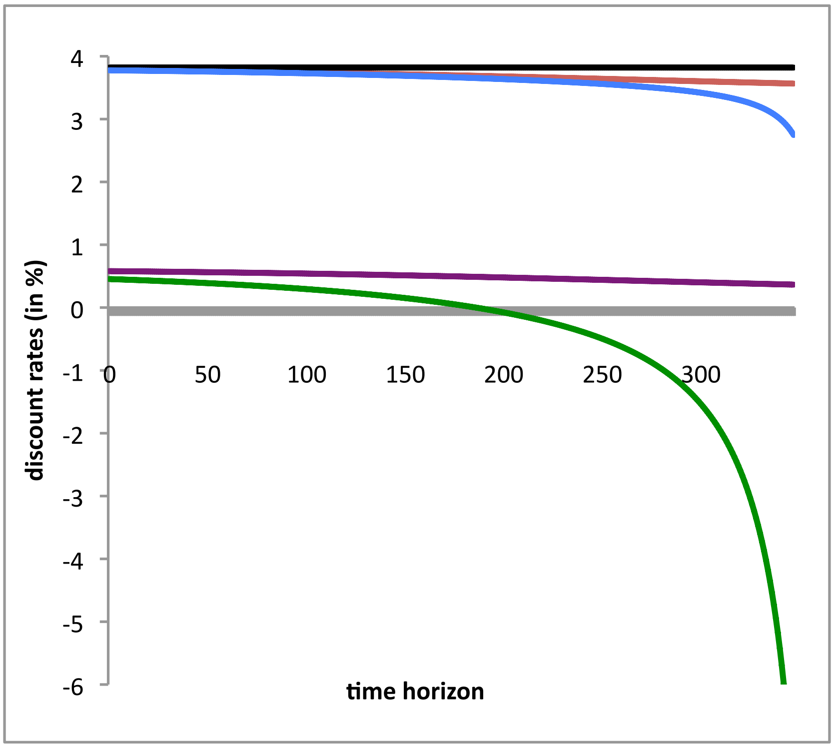

Figure 5: Illustration of **Example 4**. Description as in Figure 2.

Figure 5 shows that the initial 'relative price effect' is a bit smaller than before, but with 3.2% still substantially higher than as suggested in Baumgärtner et al. (2014f). It further illustrates that in the CES case for $\theta < 0$ and $\eta > (1 - \theta)$, the discount rates of both goods (red, purple) decline over time. In the case with a subsistence requirement, both good-specific discount rates (blue, green) decline as well and approach negative infinity as the consumption of ES is reduced towards the amount required for subsistence.

4 Discussion and Conclusions

This paper has examined the case of limited substitutability between ecosystem services and manufactured consumption goods and its implications for the appraisal of environmental policies. Specifically, I have gathered all empirical evidence available on substitution possibilities and have argued that these are ultimately restricted by subsistence requirements in terms of water, food and life-enabling ecosystem conditions. Further, I have extended dual discounting models to include such a subsistence requirement.

I find that the surveyed estimates on the elasticity of substitution – based mainly on income elasticities in contingent valuation studies – suggest that ecosystem services are currently to be considered as substitutes for manufactured goods. However, empirical evidence regarding substitutability is rather scarce despite being crucial for many different applications. This scarcity may stem from a previous low priority for such an investigation, while it may also be due to the fact that eliciting elasticities of substitution is not as straightforward. Since all of the indirect approaches of inferring the elasticity of substitution are derived from non-market valuation techniques, they share their shortcomings (Horowitz 2002; Schläpfer 2008). Despite these limitations, the importance of considering limits to substitution in applied modelling and ultimately for policy advice calls for new empirical studies, building in particular on revealed preference studies and choice experiments, whose potential has not yet been fully harnessed.

Further, I find that the inclusion of a subsistence requirement in terms of ecosystem services leads to a simple extension to the formula determining the difference in discount rates for the manufactured good and ecosystem service (also called the 'relative price effect'). This extension produces results similar to the standard non-subsistence models in the case where the subsistence threshold is not approached, i.e. for positive growth rates of ecosystem services. If, however, the provision of ecosystem services is in decline – as suggested by empirical evidence – the model produces markedly different results compared to the non-subsistence model. In particular, I find that in such a case the 'relative price effect' is not constant but grows potentially without bound as the availability and consumption of ecosystem services declines towards the subsistence level.

My analysis is relevant in several respects:

First, the discussion of substitution possibilities and the presented scenario analyses support recent findings on the difference in discount rates to be used to evaluate manufactured good and ecosystem service streams affected by (public) projects by Baumgärtner et al. (2014f), based on which one can argue that environmental cost-benefit studies should systematically value these two components differently. While Baumgärtner et al. (2014f) provide a conservative estimate of the difference in discount rates of about 1 percentage point, the numerical examples considered here suggests that if the supply of ES is in decline and substitution possibilities are, on aggregate, rather limited (cf. Examples 3 and 4), this conservative estimate should be corrected by up to four percentage points. Moreover, if we require some ES for subsistence and the availability of ES is approaching critical levels, this difference can become substantial. Overall, this provides a stronger reason for public authorities to consider ecological or dual discounting in their standard practice manuals and actual project evaluations.

Second, as an extension to my analysis, the presented modelling framework will lead to directly relevant implications for the design of an inter-temporally efficient climate policy: As a result of the subsistence threshold, the 'relative price effect' of ecosystem services will rise over time if the consumption of ecosystem services declines due to damages from climate change and the optimal level of climate change mitigation actions will thus be higher than suggested in previous integrated assessment studies (cf. Nordhaus 2008; Stern 2007; Sterner and Persson 2008).

Third, the results are of relevance to the discussion on non-constant, in particular declining discount rates (Arrow et al. 2013; Groom et al. 2005): I show that the case for declining rates already under a situation of certainty is stronger than as presented in Traeger (2011) due to the subsistence threshold.

Fourth, and relatedly, this paper's specification of intertemporal welfare relates to the discussion on the intensely debated notions of 'planetary boundaries' in general (Rockström et al. 2009) and 'catastrophic' climate change more specifically (Millner 2013; Weitzman 2009). In my setting, 'catastrophic' climate change would be conceptualized as the loss of ecosystem services required for subsistence, such as an adequate food supply, fresh water, and life-enabling ecosystem conditions. This certainly does not imply that a focus on fat-tailed probability distributions of climate damages is superfluous, but that more effort should be channelled into discussing the substance of the notion of 'catastrophe'. Naturally this also relates to an obvious limitation of the current analysis – that it is set in a deterministic context and thus does not allow for the pervasive influence of uncertainty inherent in long-term sustainability problems. This limitation needs to be addressed in future research, e.g. using viability analysis (Baumgärtner and Quaas 2009; Steinacher et al. 2013) and it also calls for analyzing suitable management strategies for the case of uncertainty, such as the application of safe minimum standards (Ciriacy-Wantrup, 1952). Despite this caveat, it already follows as an implication of my model under certainty that an inter-temporally optimal trade-off between ecosystem services and manufactured goods can only be obtained if climate mitigation (and adaptation) policies are developed in a way that first and foremost secures the provisioning of these subsistence services. The exact basket of such subsistence requirements has to be further determined by scientific and ultimately societal and political discussions.

Finally, and more generally, the presented subsistence-substitutability model reconnects the study of an efficient and just intertemporal allocation to the core of the original notion of sustainability (WCED 1987) by emphasizing the importance of basic needs, or the related notion of subsistence requirements as considered here.

Appendix

A.1 Derivation of the good-specific discount rates

To derive the good-specific discount rates $\rho_E(t)$ and $\rho_C(t)$, we first have to gather the necessary inputs:
The FOCs of $u(E, C, t)$

$$u_E = \alpha(E_t - \overline{E})^{\theta-1}\left[\alpha(E_t - \overline{E})^{\theta} + (1-\alpha)C_t^{\theta}\right]^{\frac{1-\eta-\theta}{\theta}} \tag{A.13}$$

$$u_C = u_E = (1-\alpha)C_t^{\theta-1}\left[\alpha(E_t - \overline{E})^{\theta} + (1-\alpha)C_t^{\theta}\right]^{\frac{1-\eta-\theta}{\theta}} \tag{A.14}$$

and SOCs

$$u_{EE} = -\alpha(E_t - \overline{E})^{\theta-2}\left(\alpha\eta(E_t - \overline{E})^{\theta} + (1-\theta)(1-\alpha)C_t^{\theta}\right)\left[\alpha(E_t - \overline{E})^{\theta} + (1-\alpha)C_t^{\theta}\right]^{\frac{1-\eta-2\theta}{\theta}} \tag{A.15}$$

$$u_{CC} = -(1-\alpha)C_t^{\theta-2}\left(\alpha(1-\theta)(E_t - \overline{E})^{\theta} + \eta(1-\alpha)C_t^{\theta}\right)\left[\alpha(E_t - \overline{E})^{\theta} + (1-\alpha)C_t^{\theta}\right]^{\frac{1-\eta-2\theta}{\theta}} \tag{A.16}$$

$$u_{EC} = u_{CE} = (1-\alpha)\alpha C_t^{\theta-1}(E_t - \overline{E})^{\theta-1}(1-\eta-\theta)\left[\alpha(E_t - \overline{E})^{\theta} + (1-\alpha)C_t^{\theta}\right]^{\frac{1-\eta-2\theta}{\theta}} \tag{A.17}$$

are used to derive the respective elasticities of marginal utility

$$\psi_{EE} := -\frac{u_{EE}(\cdot)E_t}{u_E(\cdot)} = \frac{E_t}{E_t - \overline{E}}\left[\frac{\alpha\eta(E - \overline{E})^{\theta} + (1-\alpha)(1-\theta)C_t^{\theta}}{\alpha(E_t - \overline{E})^{\theta} + (1-\alpha)C_t^{\theta}}\right] \tag{A.18}$$

$$\psi_{CC} := -\frac{u_{CC}(\cdot)C_t}{u_C(\cdot)} = \frac{\alpha(1-\theta)(E - \overline{E})^{\theta} + (1-\alpha)\eta C_t^{\theta}}{\alpha(E_t - \overline{E})^{\theta} + (1-\alpha)C_t^{\theta}} \tag{A.19}$$

$$\psi_{EC} := -\frac{u_{EC}(\cdot)C_t}{u_E(\cdot)} = \frac{(1-\alpha)C_t^\theta(\eta+\theta-1)}{\alpha(E_t-\overline{E})^\theta+(1-\alpha)C_t^\theta} \tag{A.20}$$

$$\psi_{CE} := -\frac{u_{CE}(\cdot)E_t}{u_C(\cdot)} = \frac{\alpha E(E-\overline{E})^{\theta-1}(\eta+\theta-1)}{\alpha(E_t-\overline{E})^\theta+(1-\alpha)C_t^\theta}\,. \tag{A.21}$$

Using these, the good-specific discount rates are given by (cf. Equations (6) and (7)):

$$\rho_E(t) = \delta + \frac{E_t}{E_t-\overline{E}}\frac{\alpha\eta(E-\overline{E})^\theta+(1-\alpha)(1-\theta)C_t^\theta}{\alpha(E_t-\overline{E})^\theta+(1-\alpha)C_t^\theta}g_E + \frac{(1-\alpha)C_t^\theta(\eta-(1-\theta))}{\alpha(E_t-\overline{E})^\theta+(1-\alpha)C_t^\theta}g_C \tag{A.22}$$

and

$$\rho_C(t) = \delta + \frac{\alpha(1-\theta)(E-\overline{E})^\theta+(1-\alpha)\eta C_t^\theta}{\alpha(E_t-\overline{E})^\theta+(1-\alpha)C_t^\theta}g_C + \frac{\alpha E(E-\overline{E})^{\theta-1}(\eta-(1-\theta))}{\alpha(E_t-\overline{E})^\theta+(1-\alpha)C_t^\theta}g_E\,. \tag{A.23}$$

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