Ramsey discounting of ecosystem services

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Abstract: Most ecosystem services which are essential for human well-being are globally declining, while the production of market goods and services, measured by GDP, is still continuously increasing. To adequately address this opposite development in public cost-benefit analyses, it has been proposed – based on an extension of the classical Ramsey model – to apply good-specific discount rates for market consumption goods and ecosystem services. Using empirical data for ten ecosystem services and five countries as well as the world at large, we estimate by how much discount rates for ecosystem services should deviate from the discount rate for market goods and services. In a conservative estimate, we find that ecosystem services in all countries should be discounted at rates that are significantly lower than the ones for market consumption goods. On global average, ecosystem services should be discounted at a rate that is 0.9±0.3 %-points lower than the one for market consumption goods.

JEL-Classification: Q28, Q51, Q57

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1 Introduction

The Millennium Ecosystem Assessment (2005) found that 15 out of 24 ecosystem services, which are essential for human well-being, are globally declining. In contrast, the production of market goods and services, measured by GDP, is still continuously growing. To adequately address this opposite development in public cost-benefit analyses, it has been suggested, based on a two-goods-extension of the classical model of Ramsey (1928), to use dual discount rates for market consumption goods and for ecosystem services (Gerlagh and van der Zwaan 2002, Tol 2003, Weikard and Zhu 2005, Hoel and Sterner 2007, Heal 2009, Kögel 2009, Gollier 2010, Guéant et al. 2010, Echazu et al. 2011, Traeger 2011).

Taking the Ramsey model as a starting point, we employ a utility function with constant elasticity of substitution between market goods and ecosystem services. We show that the difference in the two good-specific discount rates increases with the difference between the growth rates of market goods and of ecosystem services, and with the degree of complementarity between the two. The larger this difference, the lower the discount rate for ecosystem services compared to the one for market goods.

In order to empirically quantify the difference, we analyze time-series data for the period 1950–2010 on ten ecosystem services in five countries (Brazil, Germany, India, Namibia, UK) as well as for the world at large, including provisioning services (crop production, livestock production, fishery production, roundwood production, renewable water availability), regulating services (pollination, forest services, status of populations and biodiversity) and cultural services (landscape connectedness, forest area, status of endangered species), to identify country- and ecosystem-service-specific (positive or negative) growth rates. We take data on GDP-growth from the World Bank (2011c). As for an empirical estimate of the degree of substitutability between market consumption and ecosystem services, we employ a theoretical result of Ebert (2003) that links the elasticity of substitution to the income elasticity of marginal willingness to pay for ecosystem services, and empirical data from the meta-study of Jacobsen and Hanley (2009) of how willingness-to-pay for ecosystem services depends on income.

In a conservative estimate, we find that, depending on the type of ecosystem service and the country, ecosystem services should be discounted at rates that vary between 3.6±1.4 %-points lower than the one for market consumption (cultural services in India) and 0.8±0.3 %-points higher than the one for market consumption goods (provisioning services in Germany). In all five countries studied, aggregate ecosystem services should be discounted at a rate that is significantly lower than the one for market consumption, with the difference between the two discount rates ranging from 0.5±0.3 %-points (Brazil) to 2.1±0.9 %-points (India). On global average over all ecosystem services studied, we find that ecosystem services should be discounted at a rate that is 0.9±0.3 %-points lower than the one for market consumption goods.

The paper is organized as follows. In Section 2, we elaborate the theoretical background of our analysis: we introduce a model, and derive and discuss the formula to be used for the empirical estimates. In Section 3, we describe the data that we use in the empirical analysis and the analytical procedure. In Section 4, we present the results of the empirical analysis. In Section 5, we critically discuss a number of systematic, yet unavoidable, biases in our analysis. Section 6 concludes.

2 Theoretical background

Our analysis is based on the classical growth model of Ramsey (1928), which is expanded to account for heterogeneous consumption goods (Gerlagh and van der Zwaan 2002, Tol 2003, Weikard and Zhu 2005, Hoel and Sterner 2007, Heal 2009, Kögel 2009, Gollier 2010, Guéant et al. 2010, Echazu et al. 2011, Traeger 2011). As the model serves to derive a formula that can be empirically estimated (in Section 4 below), and there exists no reliable data whatsoever on the uncertainty of ecosystem-services-growth, our model neglects uncertainty altogether and is strictly deterministic.[1]

There is an infinitely lived agent who has perfect knowledge about the future and acts as a trustee on behalf of both present and future generations. The agents' objective

[1]Some of the contributions quoted here have theoretically taken into account uncertainty of ecosystem-service-growth and risk-aversion of the decision-maker (e.g. Gollier 2010).

is to maximize the intertemporal discounted-utilitarian social welfare function

$$W = \int_{t=0}^{\infty} U(C_t, E_t)\, e^{-\rho t}\, dt \ , \tag{1}$$

where $\rho > 0$ is the (constant) rate of pure time preference, that is, the rate at which utility is discounted, and $U(C_t, E_t)$ is the instantaneous utility function representing the agents preferences over the consumption of a manufactured good, C_t, and an ecosystem service, E_t, at time t. Both goods may be composites. The function $U(\cdot, \cdot)$ is assumed to have standard properties: it is twice continuously differentiable, exhibits strictly positive and decreasing marginal utility in both arguments, and is strictly quasi-concave. Let U_C and U_E denote the first partial derivatives of $U(\cdot, \cdot)$ with respect to the first and second argument, respectively, and U_{CC}, U_{CE}, U_{EC}, U_{EE} the second partial derivatives.

From the first-order conditions of the optimal control problem one can derive good-specific discount rates for the manufactured good and for the ecosystem service, that is, discount rates that measure the rate of change of the present value of the marginal utility of consumption of the respective good along the optimal consumption path (Heal 2009: Equation 2):

$$r_C = \rho + \eta_{CC}\, g_C + \eta_{CE}\, g_E \ , \tag{2}$$

$$r_E = \rho + \eta_{EE}\, g_E + \eta_{EC}\, g_C \ , \tag{3}$$

where g_C and g_E denote the growth rates of manufactured-good consumption and of ecosystem-service consumption, respectively:

$$g_C := \frac{dC_t/dt}{C_t} \ , \tag{4}$$

$$g_E := \frac{dE_t/dt}{E_t} \ , \tag{5}$$

and η_{CC} (η_{EE}) is the elasticity of marginal utility of manufactured-good (ecosystem-service) consumption with respect to manufactured-good (ecosystem-service) consumption, and η_{EC} (η_{CE}) is the elasticity of marginal utility of manufactured-good (ecosystem-service) consumption with respect to ecosystem-service (manufactured-good) consumption:

$$\eta_{CC} \;:=\; -\frac{U_{CC}(C_t, E_t)\, C_t}{U_C(C_t, E_t)} > 0 \;, \tag{6}$$

$$\eta_{EE} \;:=\; -\frac{U_{EE}(C_t, E_t)\, E_t}{U_E(C_t, E_t)} > 0 \;, \tag{7}$$

$$\eta_{CE} \;:=\; -\frac{U_{CE}(C_t, E_t)\, E_t}{U_C(C_t, E_t)} \gtreqless 0 \;, \tag{8}$$

$$\eta_{EC} \;:=\; -\frac{U_{EC}(C_t, E_t)\, C_t}{U_E(C_t, E_t)} \gtreqless 0 \;. \tag{9}$$

The own elasticities, η_{CC} and η_{EE}, are positive numbers, which means that an increased consumption of either good *ceteris paribus* strictly decreases the marginal utility of that good. In contrast, the cross elasticities, η_{CE} and η_{EC} are zero if the utility function is additively separable and can otherwise have either sign, depending on whether the two goods are substitutes or complements.

Specifically, we assume that the instantaneous utility function $U(\cdot, \cdot)$ is characterized by a constant elasticity of substitution between the manufactured good and the ecosystem service:

$$U(C_t, E_t) = \left(\alpha C_t^{\frac{\sigma-1}{\sigma}} + (1-\alpha)\, E_t^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \quad \text{with} \quad 0 < \alpha < 1,\; 0 < \sigma < +\infty \;, \tag{10}$$

where α is the relative weight of manufactured-good consumption in instantaneous utility and σ is the (constant) elasticity of substitution between the manufactured good and the ecosystem service. For $\sigma > 1$ the manufactured good and the ecosystem service are substitutes in consumption and the cross elasticities η_{CE} and η_{EC} are positive; for $\sigma < 1$ the two goods are complements and the cross elasticities are negative. For $\sigma = 1$ utility function (10) becomes the Cobb-Douglas function.

In this model, the difference between the good-specific discount rates of the manufactured good and of the ecosystem service is given by (see Appendix A.1)

$$\Delta r := r_C - r_E = \frac{1}{\sigma}\left(g_C - g_E\right) \;. \tag{11}$$

Equation (11) implies that the ecosystem service and the manufactured good have exactly the same good-specific discount rate, $\Delta r = 0$, if the two are perfect substitutes in consumption, $\sigma \to +\infty$, or if consumption of the two goods grows at at the same rate, $g_E = g_C$. If, in contrast, the manufactured good and the ecosystem service are less than perfect substitutes in consumption, $\sigma < +\infty$, the difference in good-specific discount rates may be positive or negative, $\Delta r > 0$ or $\Delta r < 0$, depending on whether consumption of the manufactured good grows at a higher or lower rate than that of the ecosystem service, $g_C > g_E$ or $g_C < g_E$.

In particular, the discount rate for the ecosystem service is lower than the one for the manufactured good, $\Delta r > 0$, if the two goods are less than perfect substitutes in consumption, $\sigma < +\infty$, and the consumption of ecosystem services grows at a lower rate than the consumption of the manufactured good, $g_E < g_C$. In this case, the difference in good-specific discount rates, Δr, increases with the inverse elasticity of substitution, $1/\sigma$, that is, with the degree of complementarity between the two goods, and with the difference in growth rates, $g_C - g_E$.

While the rate of pure time preference, ρ, of course, influences both good-specific discount rates, r_C and r_E (Equations 2 and 3), it does not influence the difference of the two discount rates, Δr (Equation 11). The reason is that the rate of pure time preference linearly adds to both discount rates and, hence, exactly cancels out when subtracting one from the other. Our analysis is, therefore, completely independent of exactly what rate of pure time preference one deems appropriate.

3 Data and data analysis

To quantitatively assess the growth rate of all different kinds of ecosystem services in different countries is a Herculean task, which not even the Millennium Ecosystem Assessment (2005) was able to accomplish. With few exceptions there are no standardized ways of identifying, measuring and reporting ecosystem services. Among these exceptions are the provisioning services that come mainly from agricultural production. Data on crop, livestock and roundwood production, capture fisheries, aquaculture and water supply is very well and consistently documented over the past decades on the global and the national scales. In contrast, the existing knowledge about the status and trends of regulating and cultural ecosystem services is very fragmented and comes, if at all, in inconsistent conceptualizations and metrics.

Against this background, our analysis is based on a selection of ecosystem services and countries that should reflect importance and representativeness on the one hand, and that is restricted by data availability on the other.[2] We aim to identify a constant annual growth rate for each ecosystem service in each country over the period 1950–2010 – or the largest most recent sub-period where data are available and a constant (positive or negative) growth trend exists.

3.1 Selection of ecosystem services and countries

As for countries, we look at two developed countries (Germany, UK), one newly industrialized country (Brazil) and two developing countries (India, Namibia) – where the categorization is that of CIA (2011), which is based on GDP per capita as well as on the Human Development Index (UNDP 2011). These five countries not only represent different degrees of development, but also very different biomes – including desert, savannah, tropical as well as temperate forests, estuarines, etc. In addition to these five countries, we look at the world at large. To include a higher number of less developed countries in the sample would have been desirable, as a large share of the world population lives in such countries and people in less developed countries typically rely to a larger extent on ecosystem services for their well-being than in more developed countries, but data availability in these countries was simply too poor.

For each country as well as the world at large, we study ten different ecosystem services of the major types provisioning, regulating and cultural services. Table 1 gives an overview of the ecosystem services considered in the analysis, and the indicators by which they are taken into account. As for provisioning services, we study the provision of food (indicated by crop, livestock and fishery production), fiber (indicated by roundwood production) and water (indicated by the availability of renewable water resources).

While data availability is excellent for these provisioning services, regulating and

[2]We discuss this selection bias due to data availability in detail in Section 5.

Table 1: Ecosystem services considered in the analysis, and indicators by which they are taken into account.

ecosystem service	indicator	unit of measurement
provisioning services		
food		
crop	crop production	tonne per year
livestock	livestock production	tonne per year
fishery	total fishery production	tonne per year
fiber	roundwood production	meter^3 per year
water	renewable water resources	kilometer^3 per year
regulating services		
pollination	beehives	number
other	forest area	hectare
	Living-Planet-Index	dimensionless
	Red-List-Index/ nat'l biodiversity indicator	various
cultural services		
	landscape connectedness	kilometer
	forest area	hectare
	Living-Planet-Index	dimensionless
	Red-List-Index/ nat'l biodiversity indicator	various

Explanation: The indicator "landscape connectedness" is calculated as the inverse of a country's road density, which is the total length of a country's road network (in km) divided by the the country's land area (in kilometer^2).

cultural services are up to date not very well documented. For these types of services, we therefore revert to a number of proxy indicators. As for regulating services, we study the indicators number of beehives (as a proxy for pollination) as well as forest area, the Living-Planet-Index and a biodiversity indicator (with the Red-List-Index worldwide and various national biodiversity indicators where available)[3]. These latter indicators can be taken as proxy for what one may think of as "ecosystem health" – a precondition for regulating ecosystem services.

As for cultural services, which are even more elusive and highly region-specific, the indicators landscape connectedness (measured as the inverse of a country's road density)[4], forest area, the Living-Planet-Index and a biodiversity indicator (with the Red-List-Index worldwide and various national biodiversity indicators where available) are taken as proxy for universal aesthetic, recreational and educational services.

3.2 Data on human population development

Since the model employed here (cf. Section 2) has one single infinitely-lived agent maximizing welfare, data on the consumption of rival goods and services has to be on a per-capita basis. In contrast, for public goods and services we can use total numbers. To calculate per-capita consumption amounts in each year, we use time-series data from the United Nations Department of Economic and Social Affairs (UN 2011) on the actual population size of all countries and the world at large over the time period studied.

In order to ensure consistent population numbers for per-capita data, we do not use existing per-capita data from different sources, as they may involve inconsistent population data. Rather, we use total numbers for all goods and services studied here from different sources, and consistently use one and the same population data set (from UN 2011) to calculate per-capita numbers.

[3]Established and well documented national biodiversity indicators exist for Germany and the UK.

[4]Road density is calculated as the total length of a country's road network divided by the the country's land area

3.3 Data on ecosystem services

Databases for time-series data were chosen based on their reliability and that time series span long periods of time. The minimum length of time series is 10 years of data. Some data series start as early as the 1950's. The United Nations Food and Agriculture Organization (FAO), the World Bank and national governments provide most of the used data. Since it is hard to find sound figures on biodiversity over a longer time period, data sources recommended in the COP8 Decision VIII/15 by the CBD (2006) parties are used for biodiversity indicators. Table 2 specifies the data sources for all data used to calculate the ecosystem-service indicators.

In all data series for rival ecosystem services, total numbers are divided by population size (with data from UN 2011) to obtain per-capita numbers.

Table 3 specifies the details on the time-series data employed for all ecosystem services. In the first column, with the ecosystem service, we specify in brackets whether we used per-capita or total numbers to estimate the growth trend for this service in the all countries. The time period in parentheses is the period over which time series data are available from that source. The time period underneath is the time period of the current growth trend over which we estimate the constant annual growth rate.

Table 2: Data sources for ecosystem-service indicators.

indicator	data source
crop production	FAO (2011c)
livestock production	FAO (2011e)
total fishery production	FAO (2011g)
roundwood production	FAO (2011b)
renewable water resources	FAO (2011a) for countries; UNEP (2011), added up over subregions, for world
beehives	FAO (2011d)
total forest area	FAO (2011f) for all countries but Germany, DESTATIS (2011) for Germany,
Living-Planet-Index (LPI)	WWF (2010: 20) for world, WWF (2010: 77) for countries; with Germany, UK = high-income countries; Brazil, India, Namibia = middle-income countries
landscape connectedness	
length of road network	World Bank (2011b)
land area	World Bank (2011a)
Red-List-Index (RLI)	Hoffmann et al. (2010) for birds, mammals, amphibians worldwide; no index time-series available for countries;
national biodiversity index	DESTATIS (2010: 16) for Germany, UK DEFRA (2011a,b) for UK; no index time-series available for other countries

Table 3: Time series data for ecosystem services.

	Brazil	Germany	India	Namibia	UK	World
crop production	(1961–2008)	(1961–2009)	(1961–2009)	(1961–2008)	(1961–2008)	(1961–2009)
[per capita]	1965–2007	1961–2008	1963–2009	1992–2008	1996–2008	1963–2007
livestock production	(1961–2008)	(1961–2008)	(1961–2008)	(1961–2008)	(1961–2008)	(1961–2009)
[per capita]	1961–2007	1993–2007	1963–2008	1963–2006	1985–2008	1993–2007
total fishery production	(1950–2009)	(1950–2009)	(1950–2009)	(1950–2009)	(1950–2009)	(1950–2009)
[per capita]	1995–2008	1967–2009	1951–2007	1993–2009	1950–2009	1950–2009
roundwood production	(1961–2008)	(1961–2008)	(1961–2008)	(1961–2008)	(1961–2008)	(1961–2008)
[per capita]	1996–2007	1993–2006	1974–2008	1984–2008	1963–2008	1961–2009
renewable water resources	(1989/1998)	(1989/1998)	(1989/1998)	(1989/1998)	(1989/1998)	(1958–2010)
[per capita]	1989/1998	1989/1998	1989/1998	1989/1998	1989/1998	1958–2012
beehives	(1961–2009)	(1961–2009)	(na)	(na)	(1961–1987)	(1961–2009)
[per capita]	1991–2008	1988–2009	na	na	1961–1987	1963–2008
total forest area	(1990–2008)	(1971–2007)	(1990–2008)	(1990–2008)	(1990–2008)	(1990–2008)
[total]	1990–2008	1991–2007	1990–2008	1990–2008	2000–2008	1990–2008
Living-Planet-Index (LPI)	(1970–2007)	(1970–2007)	(1970–2007)	(1970–2007)	(1970–2007)	(1970–2007)
[total]	1972–2006	1971–2007	1972–2006	1972–2006	1971–2007	1970–2007
landscape connectedness	(1990–2004)	(1995–2010)	(1990–2008)	(1990–2000)	(1990–2008)	(na)
[total]	1990–2004	1995–2010	1991–2007	1992–1999	1992–2007	na
Red-List-Index (RLI)	(na)	(na)	(na)	(na)	(na)	(1980–2008)
[total]	na	na	na	na	na	1980–2008
national biodiversity index	(na)	(1990–2008)	(na)	(na)	(1970–2010)	(na)
[total]	na	1991–2008	na	na	1976–2009	na

3.4 Data on manufactured goods and services

Consumption of manufactured and market-traded consumption goods and services is measured as per-capita gross domestic product, measured in purchasing-power-parities-adjusted 2005-US-dollars. Data on the gross domestic product for all countries as well as for the world at large over the time period 1980–2009 comes from the *World Development Indicators* database (World Bank 2011d). From these data, we subtract the agricultural share of GDP (reported by World Bank 2011c), to avoid double counting of market-traded provisioning ecosystem services. For, all agricultural produce is taken into account explicitly in our analysis as (provisioning) ecosystem services. The numbers thus obtained for total GDP are then divided by population size (with data from UN 2011) to obtain per-capita GDP.

3.5 Measuring growth rates

For each ecosystem service and country the full time series data is graphically depicted. If the entire graph does not show a consistent (positive or negative) growth trend, but a reversal of trend at some point, this point in time and the time period of the current trend is identified by eye's inspection. Next, an exponential function is fitted to the data over the time period thus identified (using Microsoft Excel), to identify the constant annual growth rate that best describes the current trend. Table 3 reports for all ecosystem services the time interval which displays the current trend and over which the growth rate is estimated.

To estimate the error in the growth rate thus measured, the start year and the end year of the fit are varied and, again, a constant growth rate is obtained for each varied period. Thus, maximal and minimal growth rates are identified. The average of the two extremes is used as the best estimate of the annual growth rate for the following calculation. Its standard deviation is obtained as half of the difference between this average and one of the extreme values.

3.6 Aggregation and averaging of ecosystem services

The various ecosystem services studied here are hierarchically categorized (Table 1) following the categorization of the Millennium Ecosystem Assessment (2005). At the top level, ecosystem services are categorized in provisioning, regulating and cultural services. Provisioning services comprise food, fiber and water provision. Food provision comprises crop, livestock and fishery production.

For each category of services, the growth rate is calculated as the unweighted arithmetic mean of the different growth rates of ecosystem services classified in this category. That is, the growth rate of food provisioning services is calculated as the unweighted arithmetic mean of the growth rates of crop production, livestock production and fishery production; the growth rate of provisioning services is calculated as the unweighted arithmetic mean of the growth rates of food, fiber and water provision; and the growth rate of aggregate ecosystem services is calculated as the unweighted arithmetic mean of the growth rates of provisioning, regulating and cultural services.

We take the unweighted mean at each level, rather than weighting the different services with weights that correspond to, say, their relative share in actual consumption, because in the simple model on which this analysis of discount rates is based (Section 2), ecosystem services are a homogenous good. In particular, all different, more specific ecosystem services that fall under the aggregate of "ecosystem services" are assumed to have the same elasticity of substitution with respect to manufactured consumption goods.[5]

3.7 Data on substitutability

The elasticity of substitution between manufactured consumption goods and ecosystem services, σ (as defined by Equation 10), can be estimated indirectly. Ebert (2003: 452–453) has shown that for the case of the CES utility function (10), the income elasticity of the marginal willingness to pay (WTP) for the ecosystem service is simply given by

[5]Different ecosystem services do not need to be perfect substitutes to each other, though, as long as they all have the same elasticity of substitution with respect to manufactured consumption goods.

$1/\sigma$.

The income elasticity of the marginal WTP for ecosystem services has already been empirically estimated, most comprehensively by Jacobsen and Hanley (2009) in a meta-study that draws on 145 different WTP-for-ecosystem-services estimates from 46 contingent-valuation studies across six continents. Using a random effects panel model, they found that, on global average and averaging over all different kinds of ecosystem services, the income elasticity of the marginal WTP for ecosystem services is 0.38 ± 0.14. This result is consistent with other empirical evidence, as gathered also mainly from contingent-valuation studies, that the income elasticity of WTP for ecosystem services is usually between 0.1 and 0.6 (e.g. Kriström and Riera 1996, Söderqvist and Scharin 2000, Hammitt et al. 2001, Ready et al. 2002, Horowitz and McConnell 2003, Hökby and Söderqvist 2003, Liu and Stern 2008, Scandizzo and Ventura 2008, Khan 2009, Broberg 2010, Chiabai et al. 2011, Wang et al. 2011).

We therefore use $1/\sigma = 0.38 \pm 0.14$ for the analysis of aggregate ecosystem services worldwide. Lacking more specific evidence for the specific ecosystem services and countries studied here, we use this number also for all more specific ecosystem services and countries.

3.8 Error estimates and significance

To report how data uncertainty affects the validity of results, we quantitatively report systematic data errors as follows. In all empirical estimates we report, if available, (absolute) standard errors: $x = x_0 \pm \Delta x$ means that the best empirical estimate for variable x is the value x_0, with a standard error of Δx. Standard errors are not available for GDP growth rates (World Bank 2011d) and for population size (UN 2011). We therefore use these data with an implicit standard error of zero.

In aggregating ecosystem service growth rates, we determine standard errors as follows. We assume that the different ecosystem service growth rates in one category are a sample of independent measurements of the category service growth rate. That is, we take the growth rates of crop production, livestock production and fishery production as independent measurements of the growth rate of food production; we take the growth rates of food provision, fiber provision and water provision as independent measurements of the growth rate of provisioning services; and we take the growth rates of provisioning, regulating and cultural services as independent measurements of the growth rate of aggregate ecosystem services. With this, the standard error of a growth rate is calculated as the sample standard deviation from the mean growth rate:

$$\Delta x = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2} \ , \tag{12}$$

where n is the number of services in the category, x_i is the growth rate of service i, and $\bar{x}$ is the mean growth rate in the category.

When several error-laden estimates of variables are combined to calculate Δr according to Equation (11), we use standard rules for the calculation of error propagation: the absolute standard error of a sum is the sum of the absolute standard errors of summands,

$$\Delta(g_C - g_E) = \mid \Delta g_C \mid + \mid \Delta g_E \mid \ , \tag{13}$$

and the relative standard error of a product is the sum of relative standard errors of factors,

$$\frac{\Delta \left(\frac{1}{\sigma}(g_C - g_E) \right)}{\frac{1}{\sigma}(g_C - g_E)} = \left| \frac{\Delta 1/\sigma}{1/\sigma} \right| + \left| \frac{\Delta(g_C - g_E)}{g_C - g_E} \right| \ . \tag{14}$$

We take the estimate of the sign of a variable to be significant, if the variable differs from zero by more than one standard error.

In addition to reporting the standard error of the best estimate of some variable, we also report the range of values for this variable, i.e. the largest and smallest value with their standard errors, too. These extreme values highlight the most optimistic and the most pessimistic result that one could possibly infer from the data.

Table 4: Annual growth rate [in %] of per-capita GDP without agricultural products, measured in purchasing-power-parities adjusted 2005-US$.

	Brazil	Germany	India	Namibia	UK	World
GDP growth rate g_C	1.14	1.79	4.72	1.94	2.33	1.88

4 Results

The annual growth rates of manufactured-goods consumption, excluding market-traded provisioning ecosystem services, that is, per-capita GDP without agricultural products (measured in purchasing-power-parities adjusted 2005-US$), are listed in Table 4. They are used as g_C in the calculation of Δr.

Table 5 gives an overview of the growth trends of ecosystem services studied here over the time periods specified in Table 3. Green arrows pointing up indicate an average annual growth rate of an ecosystem service of more than 0.5 %. Negative average annual growth rates of more than -0.5 % are marked with red down-pointing arrows. The light green and light red arrows indicate a growing or declining trend of an ecosystem service between zero and 0.5 % and -0.5 %, respectively. Overall, negative trends (red arrows pointing down) dominate the picture, with the positive exceptions coming mostly from managed provisioning services from the agricultural sector (including forestry and fishery). This confirms he result of Millennium Ecosystem Assessment (2005), which found 15 out of 24 ecosystem services studied to be in decline.

Several provisioning ecosystem services can be classified in the category of food provisioning services. Table 6 shows the growth rates of three services (crop production, livestock production and total fishery production) which are used to calculate the arithmetic mean of the growth rate of food provisioning services. Table 6 shows that Brazil has positive growth rates of all kinds of food provisioning services. A similar trend can be observed in India and worldwide. In Germany, the range of growth rates is bigger, with two slightly positive growth rates for crop and livestock production and a negative

Table 5: Trends of ecosystem services.

	Brazil	Germany	India	Namibia	UK	World
Crop production	↑	↑ (light)	↑	↑	↓	↑ (light)
Livestock production	↑	↑ (light)	↑	↓	↓	↑
Total fishery production	↑	↓	↑	↓	↓	↑
Roundwood production	↑	↑	↓	↓	↑	↓
Renewable water resources	↓	↓	↓	↓	↓	↓
Beehives	↓	↓	NA	NA	↓ (light)	↓
Forest area	↓	↓	↑ (light)	↓	↑	↓ (light)
LPI	↓	↑ (light)	↓	↓	↑ (light)	↓
RLI/national biodiversity indicators	NA	↓ (light)	NA	NA	↓ (light)	↓ (light)
Landscape connectedness	↓ (light)	↓ (light)	↓	↓ (light)	↓	NA

Explanation: ↑ ≥ + 0.5 %   ↓ ≤ − 0.5 %   NA not assessed
0.0 % ≤ ↑ (light) ≤ + 0.5 %   - 0.5 % ≤ ↓ (light) ≤ 0.0 %

one of total fishery production. The UK has negative growth rates, but the range is not as large as it is in Germany. Namibia has the broadest range of growth rates of food provisioning services with over 6 %-points difference between the growth rates of different services. The difference between the global growth rates is just a little bit over 1 %-point. Most growth rates have very small standard errors, which is due to very good data quality as well as constancy of (positive and negative) growth trends in food provisioning services. The calculated mean growth rates of food provisioning services in Brazil and India show positive values over 1 %. The global rate is also positive. The mean growth rates in the other three countries are negative, and over −1 %. With the exception of Germany and Namibia, the sign of growth rates of food provisioning services (as either positive or negative) is significant in all countries and worldwide.

The arithmetic mean of the provisioning services' growth rates consists of the sub-

Table 6: Mean and range of annual growth rate [in %] of food provisioning services.

	Brazil	Germany	India	Namibia	UK	World
growth rate of crop production	1.99 ±0.06	0.15 ±0.03	0.59 ±0.02	1.64 ±0.13	−2.10 ±0.12	0.45 ±0.02
growth rate of livestock production	2.01 ±0.03	0.15 ±0.05	1.92 ±0.06	−2.05 ±0.07	−0.70 ±0.02	0.72 ±0.03
growth rate of total fishery production	3.09 ±0.03	−3.38 ±0.04	2.02 ±0.01	−4.63 ±0.22	−0.84 ±0.02	1.51 ±0.02
range of food prov. services growth rate	1.99 ±0.06 … 3.09 ±0.03	−3.38 ±0.04 … 0.15 ±0.05	0.59 ±0.02 … 2.02 ±0.01	−4.63 ±0.22 … 1.64 ±0.13	−2.10 ±0.12 … −0.70 ±0.02	0.45 ±0.02 … 1.51 ±0.02
mean food prov. services growth rate	2.36 ±0.36	−1.03 ±1.18	1.51 ±0.46	−1.68 ±1.82	−1.21 ±0.45	0.89 ±0.32

categories food, fiber and water provision. As the ranges in Table 7 indicate the growth trends of provisioning services vary a lot. In all countries and worldwide, some provisioning services grow at a positive rate while others grow at a negative rate. The ranges vary between 2.7 %-points (worldwide) up to over 7.2 %-points (Germany). The standard errors of the mean growth rates of provisioning services are so large that it is not possible to make a definite statement on whether provisioning services are growing or declining. Only in Namibia, there is a significantly negative growth trend.

Table 8 shows the growth rates of regulating services. The indicators (beehives, forest area, LPI, RLI/national biodiversity indicator) show a broad range of growth rates, again, within and across all countries. The ranges reveal that in Germany, India and UK, some regulating services grow at a positive rate while others grow at a negative rate. In contrast, In Brazil, Namibia and worldwide, all regulating services grow at a negative rate. The ranges of growth rates in all countries but the UK are smaller than the ranges of provisioning services growth rates, though. Growth rates of beehives

Table 7: Mean and range of annual growth rate [in %] of provisioning services.

	Brazil	Germany	India	Namibia	UK	World
	1.99	−3.38	0.59	−4.63	−2.10	0.45
range of food prov.	±0.06	±0.04	±0.02	±0.22	±0.12	±0.02
	...	...	...	...	...	...
services growth rate	3.09	0.15	2.02	1.64	−0.70	1.51
	±0.03	±0.05	±0.01	±0.13	±0.02	±0.02
mean food prov.	2.36	−1.03	1.51	−1.68	−1.21	0.89
services growth rate	±0.36	±1.18	±0.46	±1.82	±0.45	±0.32
fiber provisioning	0.68	3.90	−0.95	−1.56	2.41	−1.03
services growth rate	±0.06	±0.14	±0.02	±0.02	±0.03	±0.01
water provisioning	−2.00	−0.20	−2.10	−2.80	−0.20	−1.25
services growth rate	±0.02	±0.01	±0.00	±0.00	±0.00	±0.01
	−2.00	−3.38	−2.10	−4.63	−2.10	−1.25
range of provisioning	±0.02	±0.04	±0.00	±0.22	±0.12	±0.01
	...	...	...	...	...	...
services growth rate	3.09	3.90	2.02	1.64	2.41	1.51
	±0.03	±0.14	±0.01	±0.13	±0.03	±0.02
mean provisioning	0.35	0.89	−0.51	−2.01	0.33	−0.46
services growth rate	±1.27	±1.52	±1.07	±0.40	±1.08	±0.68

Explanation: Renewable water resources (indicating water provisioning services) is reported by (FAO 2011a) as a constant long-term average annual value, calculated from basic hydro-geo-physical data. We take this constant value for the entire time-period and divide it by population number to obtain a per-capita value. Thus, variation over time in this index is entirely due to variation of population number over time.

Table 8: Mean and range of annual growth rate [in %] of regulating services.

	Brazil	Germany	India	Namibia	UK	World
growth rate of beehives	−0.83 ±0.04	−3.00 ±0.05			−0.35 ±0.20	−0.77 ±0.01
growth rate of forest area	−0.50 ±0.00	−0.70 ±0.05	0.39 ±0.20	−0.90 ±0.00	0.54 ±0.03	−0.20 ±0.00
growth rate of LPI	−1.14 ±0.05	0.06 ±0.02	−1.14 ±0.05	−1.14 ±0.05	0.06 ±0.02	−1.28 ±0.02
growth rate of RLI / nat'l biodiversity indicator		−0.36 ±0.08			−0.32 ±0.04	−0.08
range of regulating services growth rate	−1.14 ±0.05 … −0.50 ±0.00	−3.00 ±0.05 … 0.06 ±0.02	−1.14 ±0.05 … 0.39 ±0.20	−1.14 ±0.05 … −0.90 ±0.00	−0.35 ±0.20 … 0.54 ±0.03	−1.28 ±0.02 … −0.08
mean regulating services growth rate	−0.82 ±0.18	−1.00 ±0.69	−0.38 ±0.77	−1.02 ±0.12	−0.02 ±0.21	−0.58 ±0.28

Explanation: RLI (World) reports the average growth rate of the three RLIs (birds, mammals, amphibians) presented by Hoffmann et al. (2010); no standard error information is available for RLI. National biodiversity indicator (UK) reports the average growth rate for the two national biodiversity indicators birds (UK DEFRA 2011a) and butterflies (UK DEFRA 2011b).

and RLI/national biodiversity indicator are significantly negative everywhere, while the other regulating services grow at a significantly positive rate in some countries and at a significantly negative rate in others. The standard errors of all single measurements are small, so that the sign of all growth trends is significant. The mean growth rate of regulating services is significantly negative in all countries but India and the UK, where it is not significantly different from zero.

For the cultural services indicators landscape connectedness, forest area, LPI and RLI/national biodiversity indicator, the growth rates are shown in Table 9. They have broad ranges, and the mean growth rates have higher standard errors than those of provisioning and regulating services. Because three out of four indicators are the same

Table 9: Mean and range of annual growth rate [in %] of cultural services

	Brazil	Germany	India	Namibia	UK	World
growth rate of landscape connectedness	−0.40 ±0.05	−0.06 ±0.02	−4.90 ±0.15	−0.14 ±0.12	−0.55 ±0.06	
growth rate of forest area	−0.50 ±0.00	−0.70 ±0.05	0.39 ±0.20	−0.90 ±0.00	0.54 ±0.03	−0.20 ±0.00
growth rate of LPI	−1.14 ±0.05	0.06 ±0.02	−1.14 ±0.05	−1.14 ±0.05	0.06 ±0.02	−1.28 ±0.02
growth rate of RLI / nat'l biodiversity indicator		−0.36 ±0.08			−0.32 ±0.04	−0.08
range of cultural services growth rate	−1.14 ±0.05 ... −0.40 ±0.05	−0.70 ±0.05 ... 0.06 ±0.02	−4.90 ±0.15 ... 0.39 ±0.20	−1.14 ±0.05 ... −0.14 ±0.12	−0.55 ±0.06 ... 0.54 ±0.03	−1.28 ±0.02 ... −0.08
mean cultural services growth rate	−0.68 ±0.23	−0.27 ±0.17	−1.88 ±1.57	−0.73 ±0.30	−0.07 ±0.24	−0.52 ±0.38

Explanation: RLI (World) and national biodiversity indicators (Germany, UK) as in Table 8.

ones as those for regulating services, similar effects can be recognized. All countries as the world at large have negative mean growth rates for cultural services. This result is significant in all countries but the UK, where the mean growth rate is not significantly different from zero. Landscape connectedness and the status of RLI/biodiversity are significantly declining everywhere. Concerning the ranges of cultural services growth rates, while all services grow at negative rates in Brazil, Namibia and worldwide, in all other countries some services grow at a positive rate while others grow at a negative rate. The ranges also vary a lot.

Table 10 puts provisioning, regulating and cultural services together and shows an overall picture of the growth trends of ecosystem services. Again, the growth trends of ecosystem services vary across services and countries. The growth rates range from −4.90 % (cultural services in India) to +3.90 % (provisioning services in Germany). In all countries and worldwide, the smallest growth rate is significantly negative and the largest one is significantly positive. In India, Namibia and worldwide, the mean growth rates of all service types (provisioning, regulating, cultural) are negative. In Brazil, Germany and UK, provisioning services have a positive mean growth rate, while regulating and cultural services have a negative one. The mean growth rate for aggregate ecosystem services is significantly negative in Brazil, India, Namibia and worldwide; it is not significantly different from zero in Germany and UK. The overall picture, thus, is that aggregate ecosystem services are everywhere in decline or stagnation; they are not growing at a significantly positive rate anywhere.

Table 11 puts all pieces together and shows the calculation of Δr according to Equation (11). For this purpose, g_C is taken from Table 4 and g_E from Table 10, where, again, the range and mean of g_E is reported. In a next step, g_E is subtracted from g_C. The standard errors are those of g_E because no information about the certainty of the economic growth rates could be gathered. In all countries, the mean growth rate of ecosystem services, g_E, is significantly smaller than the growth rate of GDP, g_C. This difference in growth rates ranges from 1.5 %-points in Brazil to 5.6 %-points in India. When the difference $g_C - g_E$ is multiplied by $1/\sigma$ to obtain Δr, the uncertainties get larger. Nevertheless, in all countries the mean value of Δr is significantly larger than zero. It ranges from 0.5 %-points in Brazil to 2.1 %-points in India. On a worldwide scale, Δr is 0.9 %-points.

5 Discussion

Our analysis contains a number of systematic errors that we could not avoid and that we critically discuss here.

First, our selection of ecosystem services studied is biased due to *data availability.*

Table 10: Mean and range of annual growth rate [in %] of ecosystem services.

	Brazil	Germany	India	Namibia	UK	World
	−2.00	−3.38	−2.10	−4.63	−2.10	−1.25
range of provisioning	±0.02	±0.04	±0.00	±0.22	±0.12	±0.01
	...	...	...	...	...	...
services growth rate	3.09	3.90	2.02	1.64	2.41	1.51
	±0.03	±0.14	±0.01	±0.13	±0.03	±0.02
mean provisioning	0.35	0.89	−0.51	−2.01	0.33	−0.46
services growth rate	±1.27	±1.52	±1.07	±0.40	±1.08	±0.68
	−1.14	−3.00	−1.14	−1.14	−0.35	−1.28
range of regulating	±0.05	±0.05	±0.05	±0.05	±0.20	±0.02
	...	...	...	...	...	...
services growth rate	−0.50	0.06	0.39	−0.90	0.54	−0.08
	±0.00	±0.02	±0.20	±0.00	±0.03	
mean regulating	−0.82	−1.00	−0.38	−1.02	−0.02	−0.58
services growth rate	±0.18	±0.69	±0.77	±0.12	±0.21	±0.28
	−1.14	−0.70	−4.90	−1.14	−0.55	−1.28
range of cultural	±0.05	±0.05	±0.15	±0.05	±0.06	±0.02
	...	...	...	...	...	...
services growth rate	−0.40	0.06	0.39	−0.14	0.54	−0.08
	±0.05	±0.02	±0.20	±0.12	±0.03	
mean cultural	−0.68	−0.27	−1.88	−0.73	−0.07	−0.52
services growth rate	±0.23	±0.17	±1.57	±0.30	±0.24	±0.38
	−2.00	−3.38	−4.90	−4.63	−2.10	−1.28
range of ecosystem	±0.02	±0.04	±0.15	±0.22	±0.12	±0.02
	...	...	...	...	...	...
services growth rate	3.09	3.90	2.02	1.64	2.41	1.51
	±0.03	±0.14	±0.01	±0.13	±0.03	±0.02
mean ecosystem	−0.38	−0.13	−0.92	−1.25	0.08	−0.52
services growth rate	±0.37	±0.55	±0.48	±0.39	±0.13	±0.04

Table 11: Calculation of Δr.

	Brazil	Germany	India	Namibia	UK	World
GDP growth rate g_C [%]	1.14	1.79	4.72	1.94	2.33	1.88
range of ecosystem services	−2.00	−3.38	−4.90	−4.63	−2.10	−1.28
	±0.02	±0.04	±0.15	±0.22	±0.12	±0.02
	...	...	...	...	...	...
growth rate g_E [%]	3.09	3.90	2.02	1.64	2.41	1.51
	±0.03	±0.14	±0.01	±0.13	±0.03	±0.02
mean ecosystem services growth rate g_E [%]	−0.38	−0.13	−0.92	−1.25	0.08	−0.52
	±0.37	±0.55	±0.48	±0.39	±0.13	±0.04
range of $(g_C - g_E)$ [%]	3.14	5.17	9.62	6.57	4.43	3.16
	±0.02	±0.04	±0.15	±0.22	±0.12	±0.02
	...	...	...	...	...	...
	−1.95	−2.11	2.70	0.30	−0.08	0.37
	±0.03	±0.14	±0.01	±0.13	±0.03	±0.02
mean $(g_C - g_E)$ [%]	1.52	1.92	5.64	3.19	2.25	2.40
	±0.37	±0.55	±0.48	±0.39	±0.13	±0.04
$1/\sigma$	0.38	0.38	0.38	0.38	0.38	0.38
	±0.14	±0.14	±0.14	±0.14	±0.14	±0.14
range of $\Delta r = \frac{1}{\sigma}(g_C - g_E)$	1.19	1.97	3.66	2.50	1.68	1.20
	±0.45	±0.74	±1.40	±1.00	±0.67	±0.45
	...	...	...	...	...	...
[%-points]	−0.74	−0.80	1.03	0.11	−0.03	0.14
	±0.28	±0.35	±0.38	±0.09	±0.02	±0.06
mean $\Delta r = \frac{1}{\sigma}(g_C - g_E)$ [%-points]	0.58	0.73	2.14	1.21	0.86	0.91
	±0.35	±0.48	±0.97	±0.60	±0.36	±0.35

Data on still increasing provisioning services from agriculture is excellent, while data on quickly disappearing regulating and cultural services is hardly available. Due to this bias in data availability we have probably overestimated the growth rate of ecosystem services, g_E, (or: underestimated the absolute amount of negative growth of ecosystem services) and, hence, underestimated the value of Δr.

Second, our estimate of the elasticity of substitution, σ, between ecosystem services and manufactured consumption goods is biased due to our approach of estimating $1/\sigma$ as the *income elasticity of the marginal willingness to pay* (WTP) for ecosystem services with data from a meta study of existing WTP studies (Jacobsen and Hanley 2009). This meta study draws on contingent-valuation studies that mostly focused on ecosystem services that are substitutes for manufactured consumption, rather than complements. Furthermore, Schläpfer (2006) and Schläpfer and Hanley (2006) point out that income elasticities of WTP smaller than unity (corresponding to elasticities of substitution larger than unity) may be an artifact of the current design of contingent-valuation studies. With these two deficiencies, we have probably overestimated the value of σ and, hence, underestimated the value of Δr.

Third, the theoretical framework used here (cf. Section 2) neglects *uncertainty*, in particular about the future growth of manufactured consumption goods and ecosystem services. Assuming that the growth of both goods is uncertain and follows a bivariate geometric Brownian motion with given variance around the trend growth rates g_E and g_C, Gollier (2010: Sec. 6.1) shows (for Cobb-Douglas utility function, though) that the difference in discount rates, Δr (Equation 11) includes another additive term which contains the variances of growth of ecosystem services and that of manufactured consumption goods (as well as the covariance between the two): *ceteris paribus* Δr is the larger, the larger the variance of ecosystem-services growth compared to the variance of manufactured-consumption-goods growth. While, thus, the effect of uncertainty on the discount rate difference, Δr, can be positive or negative, it seems plausible to assume that uncertainty about ecosystem-service growth is larger than that about manufactured-consumption-goods growth, so that total uncertainty adds a positive contribution to Δr. Neglecting uncertainty (due to lack of data), we have therefore probably underestimated the value of Δr.

Considering these three biases, the systematic errors thus induced into our analysis all go in the same direction: we have most probably underestimated the difference Δr in discount rates. Although we cannot tell how large this error is, it seems safe to say that our estimate of Δr is a methodologically conservative estimate, and the real value for Δr is most probably larger than the one that we report here.

6 Conclusion

In this paper, we have analyzed how the discount rate for ecosystem services should deviate from that for market goods and services. Employing a two-goods extension of the classical Ramsey-model with a constant-elasticity-of substitution utility function, we have demonstrated that the Ramsey-argument calls for using lower discount rates for ecosystem services if they are growing at lower rates than, and are less than perfect substitutes for, market consumption goods (Equation 11). The difference in the two good-specific discount rates increases with the difference in growth rates of the two, and with the degree of complementarity between the two.

In order to empirically quantify the difference in discount rates, we have used time-series data on ten ecosystem services in five countries (Brazil, Germany, India, Namibia, UK) as well as for the world at large, including provisioning services (crop production, livestock production, fishery production, roundwood production, renewable water availability), regulating services (pollination, forest services, status of populations and biodiversity) and cultural services (landscape connectedness, forest area, status of endangered species), to identify country- and ecosystem-service-specific (positive or negative) growth rates.

We find that ecosystem services in all countries should be discounted at rates that are significantly lower than the ones for market consumption goods. Depending on the type of ecosystem service and the country, ecosystem services should be discounted at rates that vary between 3.6 ± 1.4 %-points lower than the one for market consumption (cultural services in India) and 0.8 ± 0.3 %-points higher than the one for market consumption goods (provisioning services in Germany). In all five countries studied, aggregate ecosystem services should be discounted at a rate that is significantly lower than the one for market consumption, with the difference between the two discount rates ranging from 0.5±0.3 %-points (Brazil) to 2.1±0.9 %-points (India). On global average over all ecosystem services studied, we find that ecosystem services should be discounted at a rate that is 0.9±0.3 %-points lower than the one for market consumption goods.

This suggests that public cost-benefit-analyses should not use a uniform discount rate but dual discount rates – one for market consumption goods and services, and one for ecosystem services – as the difference in these two discount rates is significantly larger than zero. Our analysis suggest that on global average, a discount rate should be used for ecosystem services that is about one percent-point lower than the one for market consumption goods and services.

Our estimate of the difference in discount rates between ecosystem services and manufactured consumption goods contains a number of systematic, yet unavoidable, biases (cf. Section 5). As they all go into the same direction, we have most probably underestimated the difference in discount rates. In that it was our intention to estimate by how much ecosystem services should be discounted at *lower* rates than manufactured consumption goods, our analysis provides a methodologically conservative estimate for that purpose. This suggests to use a specific discount rate for ecosystem services that is even lower (and possibly much lower) than suggested by the numbers reported here.

Among all countries studied here, the loss of ecosystem services, and, consequently, the difference in discount rates for ecosystem services as compared to the discount rate for market consumption goods, is the largest in the developing countries (India, Namibia). This is especially disturbing as the population in developing countries tends to be generally more dependent on the various provisioning, regulating and cultural ecosystem services than the population in highly developed countries. These countries are thus facing a double challenge: while (1) ecosystem services essential for human well-being are in decline, (2) applying a lower discount rate on ecosystem services implies higher opportunity costs of economic or social development projects.

The challenge for economists and governments will be to assess and use such dual discount rates, in a context(i.e. ecosystem and country)-specific manner, to foster economically efficient and socially acceptable decisions. For this purpose, it is imperative to expand our (hitherto only very sparse) knowledge about ecosystem services, their ascertainment and their importance for human well-being (such as e.g. their substitutability with manufactured consumption goods). Up to date, there are no standardized ways of identifying, measuring and reporting ecosystem services. Endeavors such as the Millennium Ecosystem Assessment (2005) or the UK National Ecosystem Assessment (2011a,b) are the first steps in this direction, and they point the way.

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Appendix

A.1 Proof of Equation (11)

From utility function (10) one obtains (dropping the time index and the arguments of the function)

$$U_C = \alpha \left(\frac{U}{C}\right)^{\frac{1}{\sigma}} , \tag{A.15}$$

$$U_E = (1-\alpha)\left(\frac{U}{E}\right)^{\frac{1}{\sigma}} , \tag{A.16}$$

$$U_{CC} = -\frac{\alpha}{\sigma}\frac{1}{C}\left(\frac{U}{C}\right)^{\frac{1}{\sigma}}\left[1-\alpha\left(\frac{U}{C}\right)^{\frac{1}{\sigma}-1}\right] , \tag{A.17}$$

$$U_{EE} = -\frac{1-\alpha}{\sigma}\frac{1}{E}\left(\frac{U}{E}\right)^{\frac{1}{\sigma}}\left[1-\alpha\left(\frac{U}{E}\right)^{\frac{1}{\sigma}-1}\right] , \tag{A.18}$$

$$U_{CE} = U_{CE} = \frac{\alpha(1-\alpha)}{\sigma}\left(\frac{U}{CE}\right)^{\frac{1}{\sigma}} U^{\frac{1}{\sigma}-1} . \tag{A.19}$$

With these expressions, the elasticities (6)–(9) become

$$\eta_{CC} = \frac{1}{\sigma}\left[1-\alpha\left(\frac{U}{C}\right)^{\frac{1}{\sigma}-1}\right] , \tag{A.20}$$

$$\eta_{EE} = \frac{1}{\sigma}\left[1-(1-\alpha)\left(\frac{U}{E}\right)^{\frac{1}{\sigma}-1}\right] , \tag{A.21}$$

$$\eta_{CE} = -\frac{1-\alpha}{\sigma}\left(\frac{U}{E}\right)^{\frac{1}{\sigma}-1} , \tag{A.22}$$

$$\eta_{EC} = -\frac{\alpha}{\sigma}\left(\frac{U}{C}\right)^{\frac{1}{\sigma}-1} . \tag{A.23}$$

With these elasticities, the difference between the discount rates r_C (Equation 2) and r_E (Equation 3) becomes

$$\begin{aligned}
\Delta r &= r_C - r_E && \text{(A.24)}\\
&= \rho + \eta_{CC}\, g_C + \eta_{CE}\, g_E - \rho - \eta_{EE}\, g_E - \eta_{EC}\, g_C && \text{(A.25)}\\
&= (\eta_{CC} - \eta_{EC})\; g_C - (\eta_{EE} - \eta_{CE})\; g_E && \text{(A.26)}\\
&= \left(\frac{1}{\sigma}\left[1-\alpha\left(\frac{U}{C}\right)^{\frac{1}{\sigma}-1}\right] + \frac{\alpha}{\sigma}\left(\frac{U}{C}\right)^{\frac{1}{\sigma}-1}\right) g_C && \text{(A.27)}\\
&\quad - \left(\frac{1}{\sigma}\left[1-(1-\alpha)\left(\frac{U}{E}\right)^{\frac{1}{\sigma}-1}\right] + \frac{1-\alpha}{\sigma}\left(\frac{U}{E}\right)^{\frac{1}{\sigma}-1}\right) g_E && \text{(A.28)}\\
&= \frac{1}{\sigma}\, g_C - \frac{1}{\sigma}\, g_E && \text{(A.29)}\\
&= \frac{1}{\sigma}\,(g_C - g_E)\ . && \text{(A.30)}
\end{aligned}$$

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