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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 consumption goods, measured by GDP, is still growing. To adequately account for this opposite development in public cost-benefit analyses, it has been proposed—based on a two-goods extension of the Ramsey growth model—to apply good-specific discount rates for manufactured consumption goods and for ecosystem services. Using empirical data for ten ecosystem services across five countries and the world at large, we estimated the difference between the discount rates for ecosystem services and for manufactured consumption goods. In a conservative estimate, we found that ecosystem services in all countries should be discounted at rates that are significantly lower than the ones for manufactured 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 manufactured consumption goods. The difference is larger in less developed countries and smaller in more developed countries. This result supports and substantiates the suggestion that public cost-benefit-analyses should use country-specific dual discount rates—one for manufactured consumption goods and one for ecosystem services.

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1 Introduction

Ecosystem services are the directly or indirectly appropriated ecosystem structures, functions or processes that contribute to human well-being (Millennium Ecosystem Assessment 2005). This includes provisioning services such as food, fuel or water; regulating services such as climate, flood or disease control; and cultural services such as aesthetic enjoyment or spiritual fulfillment. Many of these services rendered by nature, are essential for human livelihoods. The Millennium Ecosystem Assessment (2005) found that 60 % of the ecosystem services studied are globally declining. In contrast, the production of consumption goods by humans, measured by gross domestic product (GDP), is still growing (World Bank 2011d).

   To adequately account for such opposite developments in public cost-benefit analyses of projects with economic and environmental impacts, it has been suggested to apply dual discount rates for manufactured consumption goods and for environmental impacts/services (Price 1993, 2003; Hasselmann et al. 1997; Plambeck et al. 1997; Horowitz 2002; Yang 2003).[1] Many studies over the past decade have conceptually and theoretically analyzed whether, in what manner, and to what extent this is warranted (Gerlagh and van der Zwaan 2002; Tol 2003; Weikard and Zhu 2005; Hoel and Sterner 2007; Heal 2009; Kögel 2009; Gollier 2010; Traeger 2011; Echazu et al. 2012; Guéant et al. 2012).

   From this analysis it has emerged that dual-rate discounting is warranted if relative scarcities between different goods are changing over time, yet, future consumption is valued in constant relative prices or future prices for environmental goods are unavailable. Differing discount rates then serve to account for changing relative scarcities between the different goods. In contrast, if future consumption is valued in prices that change over time to properly reflect changing relative scarcities, then a uniform discount rate (reflecting pure time preference only) is appropriate. As in most long-term public cost-benefit analyses of projects with economic and ecological impacts the economic and ecological impacts are valued in constant relative prices, i.e. changing relative scarcities are neglected in the valuation, simply because detailed information on how changing relative scarcities would in general equilibrium affect relative prices over time are missing, dual-rate discounting seems appropriate.

   Against this background, the aim of our study was to empirically estimate the difference between the discount rates for manufactured consumption goods and for ecosystem services which is due to the Ramsey-argument. According to the Ramsey rule (1928), the good-specific discount rate depends on the growth rate and the elasticity of marginal utility of that good. Therefore, discount rates of different goods should differ from each other if, and to the extent that, consumption of these goods grows at different rates and has different elasticity of marginal utility. Quantitatively estimating this difference for various ecosystems services and for various countries, should elucidate whether at all, and where, the argument is not only theoretically but also empirically significant, so as to warrant to actually use dual discount rates in practical policy-making.

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[1] The general idea of differentiating between good-specific discount rates when consumption goods are heterogenous goes back to Malinvaud (1953).

The sole empirical estimate up to now of how the "ecological discount rate" should differ from the consumption discount rate has been provided by Gollier (2010: Sect. 6). His empirical analysis is restricted in two ways.[2] First, he has not used empirical data on ecosystem services for estimating their growth rate, but made the assumption that it is negatively proportional to the growth of GDP. Second, he does not provide an empirical estimate of the elasticity of substitution between manufactured consumption goods and ecosystem services, but displays results for alternative values of 0.5, 1 and 1.5.

Our analysis closes these two gaps. It proceeded as follows. We took the Ramsey model (1928) as a theoretical starting point, where we employed a two-goods utility function with constant elasticity of substitution (CES) between manufactured consumption goods and ecosystem services, and constant intertemporal elasticity of substitution (CIES). For an empirical estimate of the (de)growth of ecosystem services, we analyzed time-series data for the period 1950–2010 of ten ecosystem services across five countries (Brazil, Germany, India, Namibia, UK) and 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 used data on GDP-growth from the World Bank (2011d). For an empirical estimate of the degree of substitutability between manufactured consumption goods and ecosystem services, we employed a theoretical result of Ebert (2003) that links the elasticity of substitution to the income elasticity of 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 found 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 manufactured consumption goods (cultural services in India) and 0.8 ± 0.3 %-points higher than the one for manufactured 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 manufactured consumption goods, 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 and aggregating over all ecosystem services studied, we found that ecosystem services should be discounted at a rate that is 0.9 ± 0.3 %-points lower than the one for manufactured consumption goods.

2 Theoretical Background

Our analysis was based on the growth model of Ramsey (1928), which was expanded to account for heterogeneous consumption goods with, in particular, CES between them in instantaneous consumption, and CIES with respect to the instantaneous aggregate consumption bundle (Guesnerie 2004; Hoel and Sterner 2007; Traeger 2011). As the model serves to derive a formula that can be empirically estimated (in Sect. 4 below), and up to today no reliable data on the uncertainty of ecosystem-services-growth exists, our model neglects uncertainty altogether and is strictly deterministic.[3]

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[2] The main motivation and achievement of his analysis are theoretical, anyway. The empirical analysis in Sect. 6 of his paper only serves as a numerical illustration of the theoretical results.

[3] 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).

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 agent's objective 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 (Weikard and Zhu 2005: Equations 11, 12; Heal 2009: Equation 2):

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

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

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

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

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

$$\epsilon_{CE} := -\frac{U_{CE}(C_t, E_t) \, E_t}{U_C(C_t, E_t)} \overset{>}{\underset{<}{=}} 0 \,, \tag{8}$$

$$\epsilon_{EC} := -\frac{U_{EC}(C_t, E_t) \, C_t}{U_E(C_t, E_t)} \overset{>}{\underset{<}{=}} 0. \tag{9}$$

The own elasticities, ϵ_{CC} and ϵ_{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, ϵ_{CE} and ϵ_{EC} are zero if the utility function is additively separable and can otherwise have either sign.

Specifically, we assumed that the instantaneous utility function $U(\cdot, \cdot)$ is characterized by a CES between the manufactured good and the ecosystem service in instantaneous aggregate consumption, and a CIES of instantaneous aggregate consumption:

$$U(C_t, E_t) = \frac{1}{1-\eta} \left(\alpha C_t^{\frac{\sigma-1}{\sigma}} + (1-\alpha) E_t^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma(1-\eta)}{\sigma-1}} \tag{10}$$

$$\text{with} \quad 0 < \alpha < 1, \ 0 < \sigma < +\infty, \ \eta \geq 0,$$

where α is the relative weight of manufactured-good consumption in instantaneous aggregate consumption, σ is the elasticity of substitution between the manufactured good and the ecosystem service in instantaneous consumption, and $1/\eta$ is the elasticity of intertemporal substitution of instantaneous aggregate consumption.[4] For $\sigma > 1$ the manufactured good and the ecosystem service are substitutes in instantaneous aggregate consumption, for $\sigma < 1$ the two goods are complements in instantaneous aggregate consumption, and for $\sigma = 1$ instantaneous aggregate consumption 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 (Hoel and Sterner 2007: Eq. 12; Traeger 2011: Eq. 7)

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

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 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 (Eqs. 2 and 3), it does not influence the difference of the two discount rates, Δr (Eq. 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.

Likewise, while the (inverse) intertemporal elasticity of substitution, η, influences both good-specific discount rates, r_C and r_E (Eqs. 2 and 3), it does not influence the difference of the two discount rates, Δr (Eq. 11). The reason is that—like the rate of pure time preference—

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[4] Strictly speaking, the function $U(C, E)$ is defined by the term on the right-hand side of Eq. (10) for all $\eta \neq 1$ (as this term is not defined for $\eta = 1$). For $\eta = 1$, $U(C, E)$ is defined by the continuous extension of this term for $\eta \to 1$, which is $\log \left(\alpha C^{(\sigma-1)/\sigma} + (1-\alpha) E^{(\sigma-1)/\sigma} \right)^{\sigma/(\sigma-1)}$.

it acts on the instantaneous aggregate consumption bundle and, thus, influences consumption of both goods in the same relative manner as long as both grow at constant rates.

3 Data and Data Analysis

To quantitatively assess the growth rates of different ecosystem services in different countries is a Herculean task, which not even the Millennium Ecosystem Assessment (2005) was able to accomplish. With few exceptions—for particular ecosystem services or particular local ecosystems—there are no standardized ways of identifying, measuring and reporting ecosystem services (Boyd and Banzhaf 2007). Among these exceptions are the provisioning services that come mainly from agricultural production. Data on crop, livestock and roundwood production, capture fishery, aquaculture and water supply is well and consistently documented over the past decades at 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 was 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.[5] Our aim was 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 there is a lot of variation among countries in the (de)growth of consumption and of ecosystem services, we not only looked at the global average but also at the country level. In particular, we looked at two developed countries (Germany, UK), one newly industrialized country (Brazil) and two developing countries (India, Namibia)—where the categorization is that of the US Central Intelligence Agency (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 comprise different biomes—including deserts, savannahs, tropical as well as temperate forests, estuaries, etc. 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 (UNDP 2011) and people in less developed countries typically rely to a larger extent on ecosystem services for their well-being than in more developed countries (TEEB 2011: Sect. 3.5), but data availability in these countries was insufficient.

For the country and the global scale we studied ten different ecosystem services of the major types provisioning, regulating and cultural services. Table 1 presents 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 studied 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).[6]

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

[6] In line with the *Common International Classification of Ecosystem Services* (Haines-Young and Potschin 2012), which is compatible with the internationally adopted *System of Environmental-Economic Accounting*

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

Ecosystem service	Rivalry	Indicator	Unit of measurement
Provisioning services			
Food			
Crop	y	Crop production	Tonne per year
Livestock	y	Livestock production	Tonne per year
Fishery	y	Fishery production	Tonne per year
Fiber	y	Roundwood production	$Meter^3$ per year
Water	y	Renewable water resources	$Kilometer^3$ per year
Regulating services			
Pollination services	y	Beehives	Number
Other	n	Forest area	Hectare
	n	Living-planet-index	Dimensionless
	n	Red-list-index/	Various
	n	Nat'l biodiversity indicator	
Cultural services			
	n	Landscape connectedness	Kilometer
	n	Forest area	Hectare
	n	Living-planet-index	Dimensionless
	n	Red-list-index/	Various
	n	Nat'l biodiversity indicator	

Explanation: (1) Rivalry: y = yes, n = no. (2) Fishery production includes capture fishery and aquaculture production. (3) The indicator "landscape connectedness" was calculated as the inverse of a country's road density, which is the total length of a country's road network (in kilometer) divided by the the country's land area (in $kilometer^2$). (4) All indicators were measured at the country-level. All indicators were measured at the country-level.

While data availability is excellent for such provisioning services, regulating and cultural services are to date not well documented. For these types of services, we therefore reverted to a number of proxy indicators. As for regulating services, we studied the indicators number of beehives (as a proxy for pollination services) 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)[7]. 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)[8], forest area, the Living-Planet-Index and a biodiversity indicator (with the Red-List-Index

Footnote 6 continued
(United Nations et al. 2012), we understand provisioning services as the *final* ecosystem services from the environment that cross the production boundary and thus become benefits in the economy. Their provision may depend on human inputs, such as e.g. capital, labor, energy and fertilizer, but they are still inextricably linked to ecosystems as they critically depend on a number of intermediate and supporting services, such as e.g. soil formation or nutrient cycling.

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

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

worldwide and various national biodiversity indicators where available) were taken as proxy
for universal aesthetic, recreational and educational services.

3.2 Data on Human Population Development

Since the model employed here (cf. Sect. 2) has one single infinitely-lived agent maximizing
welfare, data on the consumption of rival goods and services (e.g. food or fiber) has to be
on a per-capita basis. In contrast, for non-rival goods and services (e.g. climate regulation or
aesthetic beauty of landscapes) we used total numbers. To calculate per-capita consumption
amounts in each year, we used 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 did not use
existing per-capita data from different sources, as they may involve inconsistent population
data. Rather, we used 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.

3.3 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 required minimum length of time series was ten years. Some data
series start as early as in the 1950's. The United Nations Food and Agriculture Organization
(FAO), the World Bank and national governments provide most of the data used in our
analysis. Since it is difficult 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 were
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, the total number in a given year was divided
by the population size in that year (with data from UN 2011) to obtain the per-capita number.

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. The time period in
parentheses is the period over which time series data were available from that source. The
time period underneath is the period of the current growth trend over which we estimated the
constant annual growth rate (see Sect. 3.5).

3.4 Data on Manufactured Goods and Services

Production of manufactured and market-traded consumption goods was measured as per-
capita GDP in units of purchasing-power-parities-adjusted 2005-US-dollars. Data on the
GDP for all countries as well as for the world at large over the time period 1980–2009 came
from the *World Development Indicators* database (World Bank 2011d). As GDP includes
some market-traded provisioning ecosystem services—namely from agriculture, livestock
production, fisheries and forestry—we subtracted the agricultural share of GDP (reported by
World Bank 2011c),[9] to avoid double counting of these ecosystem services. The numbers

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[9] In this dataset, "agriculture" corresponds to ISIC divisions 1–5 and includes forestry, hunting, and fishing,
as well as cultivation of crops and livestock production.

Table 2 Data sources for ecosystem-service indicators

Indicator	Data source
Crop production	FAO (2011c)
Livestock production	FAO (2011e)
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)
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 and Hilton-Taylor (2010) for birds, mammals, amphibians worldwide no index time-series available for countries;
National biodiversity index	DESTATIS (2010: 16) for Germany, DERFA (2011a, b) for UK; no index time-series available for other countries

thus obtained for total GDP were 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 was graphically depicted. If the graph showed a consistent (positive or negative) growth trend over the entire period, this time period was provisionally taken to be the one from which the current growth trend can be determined. If the graph did not show a consistent (positive or negative) growth trend over the entire period, but a reversal of trend at some point, this point in time was provisionally identified by eye's inspection. In case of several reversals of trend, only the latest one was taken.

Then, to robustly determine the current growth trend, an exponential function was fitted (using Microsoft Excel) to the data over each of the nine time periods obtained from the provisional one by varying both the initial and the final year by ± 1 year, to identify the average annual growth rate over this period. The mean of these nine growth rates was taken as the annual growth rate that best describes the current growth trend. This growth rate is the one reported for the respective service and country in Tables 5, 6, 7 and 8. The time interval out of the nine intervals that yielded the growth rate closest to the mean is reported in Table 3 as the time interval which displays the current trend. If several time periods yielded the same growth rate, the longest time period was selected.

To estimate the measurement error in the growth rate, the maximal and the minimal growth rates of the nine variations over initial and final years were identified. Half of the difference between the mean and one of the extreme values was taken as the standard error of the mean

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
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)	(1961–2009)
[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)	(1961–2009)	(na)	(1961–1987)	(1961–2009)
[per capita]	1991–2008	1988–2009	na	na	1961–1987	1963–2008
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

growth rate. This standard error is also reported for the respective service and country in Tables 5, 6, 7 and 8.

3.6 Aggregation and Averaging of Ecosystem Services

The various ecosystem services studied here are hierarchically categorized (Table 1), following 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 was 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 was calculated as the unweighted arithmetic mean of the growth rates of crop production, livestock production and fishery production; the growth rate of provisioning services was calculated as the unweighted arithmetic mean of the growth rates of food, fiber and water provision; and the growth rate of aggregate ecosystem services was calculated as the unweighted arithmetic mean of the growth rates of provisioning, regulating and cultural services.

We took the unweighted mean, rather than weighting the different services with weights that correspond to, say, their relative share in actual consumption, because in the model on which this analysis of discount rates was based (Sect. 2), ecosystem services are a homogenous good. In particular, all different, more specific ecosystem services that fall under the aggregate of "ecosystem services" were assumed to have the same elasticity of substitution with respect to manufactured consumption goods.[10]

3.7 Data on Substitutability

The elasticity of substitution between manufactured consumption goods and ecosystem services, σ (as defined by Eq. 10), could be estimated indirectly (Yu and Abler 2010: 539, 551).

Ebert (2003: 452–453), generalizing an earlier result of Kovenock and Sadka (1981), has shown that for the CES utility function (10), the income elasticity of the willingness to pay (WTP) for the ecosystem service is simply given by $1/\sigma$.

The income elasticity of the 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 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. 2013).

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

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[10] 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.

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 used these data with an implicit standard error of zero.

In aggregating ecosystem service growth rates, we determined standard errors as follows. We assumed that the different ecosystem service growth rates in one category are a sample of independent measurements of the category service growth rate. In particular, we took the growth rates of crop production, livestock production and fishery production as independent measurements of the growth rate of food production; we took the growth rates of food production, fiber production and water production as independent measurements of the growth rate of provisioning services; and we took 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 was 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 were combined to calculate Δr according to Eq. (11), we used 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 its factors,

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

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

In addition to reporting the standard error of the best estimate of a 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.

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 4 Average annual growth rate [in %] over the period 1980–2009 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

Several provisioning ecosystem services can be classified in the category of food provisioning services. Table 5 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. 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 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 slightly over 1 %-point. Most growth rates have small standard errors, which is due to high 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 above 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 subcategories food, fiber and water provision. As the ranges in Table 6 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 very large. Therefore, 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 7 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 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 as an indicator of pollination services, and of the RLI/national biodiversity indicator are significantly negative in all countries, 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 8. 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 ones as those for regulating services, similar effects can be recognized. All countries as the world at

Table 5 Mean and range of annual growth rates [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	−3.38±0.04	0.59±0.02	−4.63±0.22	−2.10±0.12	0.45±0.02
	...	...	...	...	...	...
	3.09±0.03	0.15±0.05	2.02±0.01	1.64±0.13	−0.70±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

Table 6 Mean and range of annual growth rates [in %] of provisioning services

	Brazil	Germany	India	Namibia	UK	World
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
Fiber provisioning services growth rate	0.68 ± 0.06	3.90 ± 0.14	-0.95 ± 0.02	-1.56 ± 0.02	2.41 ± 0.03	-1.03 ± 0.01
Water provisioning services growth rate	-2.00 ± 0.02	-0.20 ± 0.01	-2.10 ± 0.00	-2.80 ± 0.00	-0.20 ± 0.00	-1.25 ± 0.01
Range of provisioning services growth rate	-2.00 ± 0.02 ... 3.09 ± 0.03	-3.38 ± 0.04 ... 3.90 ± 0.14	-2.10 ± 0.00 ... 2.02 ± 0.01	-4.63 ± 0.22 ... 1.64 ± 0.13	-2.10 ± 0.12 ... 2.41 ± 0.03	-1.25 ± 0.01 ... 1.51 ± 0.02
Mean provisioning services growth rate	0.35 ± 1.27	0.89 ± 1.52	-0.51 ± 1.07	-2.01 ± 0.40	0.33 ± 1.08	-0.46 ± 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, temporal variation in this index can entirely be explained by variation of population number over time

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 substantially.

Table 9 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. Overall, negative growth trends dominate the picture, with the positive exceptions coming mostly from highly managed provisioning services from the agricultural sector (including forestry and fishery). This confirms the result of Millennium Ecosystem Assessment (2005), which found 15 out of 24 ecosystem services studied to be in decline.

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 7 Mean and range of annual growth rates [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	−3.00±0.05	−1.14±0.05	−1.14±0.05	−0.35±0.20	−1.28±0.02
	...	...	...	...	...	...
	−0.50±0.00	0.06±0.02	0.39±0.20	−0.90±0.00	0.54±0.03	−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 and Hilton-Taylor (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 (DERFA 2011a) and butterflies (DERFA 2011b)

Table 8 Mean and range of annual growth rates [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	-0.70 ± 0.05	-4.90 ± 0.15	-1.14 ± 0.05	-0.55 ± 0.06	-1.28 ± 0.02
	$\ldots$	$\ldots$	$\ldots$	$\ldots$	$\ldots$	$\ldots$
	-0.40 ± 0.05	0.06 ± 0.02	0.39 ± 0.20	-0.14 ± 0.12	0.54 ± 0.03	-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 7

Table 9 Mean and range of annual growth rates [in %] of ecosystem services

	Brazil	Germany	India	Namibia	UK	World
Range of provisioning services growth rate	−2.00±0.02 ⋯ 3.09±0.03	−3.38±0.04 ⋯ 3.90±0.14	−2.10±0.00 ⋯ 2.02±0.01	−4.63±0.22 ⋯ 1.64±0.13	−2.10±0.12 ⋯ 2.41±0.03	−1.25±0.01 ⋯ 1.51±0.02
Mean provisioning services growth rate	0.35±1.27	0.89±1.52	−0.51±1.07	−2.01±0.40	0.33±1.08	−0.46±0.68
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
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
Range of ecosystem services growth rate	−2.00±0.02 ⋯ 3.09±0.03	−3.38±0.04 ⋯ 3.90±0.14	−4.90±0.15 ⋯ 2.02±0.01	−4.63±0.22 ⋯ 1.64±0.13	−2.10±0.12 ⋯ 2.41±0.03	−1.28±0.02 ⋯ 1.51±0.02
Mean ecosystem services growth rate	−0.38±0.37	−0.13±0.55	−0.92±0.48	−1.25±0.39	0.08±0.13	−0.52±0.04

Table 10 puts all pieces together and shows the calculation of Δr according to Eq. (11). For this purpose, g_C is taken from Table 4 and g_E from Table 9, 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 increase. 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. At the global scale, Δr is 0.9 %-points.

5 Discussion

One strength of our analysis is that it employs the best currently available time-series datasets for a broad range of ecosystem services and a diverse set of countries as well as the world at large. As limited and incomplete these data still are, they allowed us to perform an empirical analysis that is both broad and in-depth. As a result, our analysis shows in a robust manner the general and uniform trends in the (de)growth of ecosystem services as well as the particular developments in specific ecosystem services or countries.

Another, methodological innovation of our study is the empirical estimate of the elasticity of substitution between manufactured consumption goods and ecosystem services, where we employ the theoretical result of Ebert (2003) and the empirical meta-study of Jacobsen and Hanley (2009). Under the simplifying assumption that ecosystem services are a homogenous good in the utility function, and so are manufactured consumption goods, so that there is only one single elasticity of substitution between the two, this allowed us to estimate the (inverse) elasticity of substitution.

On the other hand, our analysis contains three systematic errors that we could not avoid. First, our selection of ecosystem services studied is biased due to *data availability*. Data on still increasing provisioning services from agriculture were excellent and easily available, while data on quickly disappearing regulating and cultural services were hardly available. Due to this bias in data availability we have probably overestimated the growth rate of ecosystem services, g_E, (that is: 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 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. Sect. 2) neglects *uncertainty*, in particular about the future growth of manufactured consumption goods and ecosystem services, due to lack of data. Assuming that the growth of both manufactured consumption goods and ecosystem services is uncertain and follows a bivariate geometric Brownian motion with given variance around the trend growth rates g_E and g_C, Gollier 2010, : Sect. 6.1 shows (for

Table 10 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 growth rate g_E [%]	-2.00 ± 0.02	-3.38 ± 0.04	-4.90 ± 0.15	-4.63 ± 0.22	-2.10 ± 0.12	-1.28 ± 0.02
	...	...	...	...	...	...
	3.09 ± 0.03	3.90 ± 0.14	2.02 ± 0.01	1.64 ± 0.13	2.41 ± 0.03	1.51 ± 0.02
Mean ecosystem services growth rate g_E [%]	-0.38 ± 0.37	-0.13 ± 0.55	-0.92 ± 0.48	-1.25 ± 0.39	0.08 ± 0.13	-0.52 ± 0.04
Range of $(g_C - g_E)$ [%]	3.14 ± 0.02	5.17 ± 0.04	9.62 ± 0.15	6.57 ± 0.22	4.43 ± 0.12	3.16 ± 0.02
	...	...	...	...	...	...
	-1.95 ± 0.03	-2.11 ± 0.14	2.70 ± 0.01	0.30 ± 0.13	-0.08 ± 0.03	0.37 ± 0.02
Mean $(g_C - g_E)$ [%]	1.52 ± 0.37	1.92 ± 0.55	5.64 ± 0.48	3.19 ± 0.39	2.25 ± 0.13	2.40 ± 0.04
$1/\sigma$	0.38 ± 0.14	0.38 ± 0.14	0.38 ± 0.14	0.38 ± 0.14	0.38 ± 0.14	0.38 ± 0.14
Range of $\Delta r = \frac{1}{\sigma}(g_C - g_E)$ [%-points]	1.19 ± 0.45	1.97 ± 0.74	3.66 ± 1.40	2.50 ± 1.00	1.68 ± 0.67	1.20 ± 0.45
	...	...	...	...	...	...
	-0.74 ± 0.28	-0.80 ± 0.35	1.03 ± 0.38	0.11 ± 0.09	-0.03 ± 0.02	0.14 ± 0.06
Mean $\Delta r = \frac{1}{\sigma}(g_C - g_E)$ [%-points]	0.58 ± 0.35	0.73 ± 0.48	2.14 ± 0.97	1.21 ± 0.60	0.86 ± 0.36	0.91 ± 0.35

Cobb-Douglas utility function, though) that the difference in discount rates, Δr (Eq. 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. If the degrees of risk aversion on both goods are equal, this additional term to Δr is simply the variance of ecosystem-services growth minus the variance of manufactured-consumption-goods growth (multiplied by the degree of risk aversion). 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, we have therefore probably underestimated the value of Δr.

Considering these three biases, the systematic errors thus induced in our analysis all go in the same direction: we have most likely 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 likely larger than the one that we report here.

6 Conclusion

We have demonstrated that the Ramsey-argument calls for using lower discount rates for ecosystem services than for manufactured consumption goods. More specifically, we have found that in all five countries studied (Brazil, Germany, India, Namibia,UK), aggregate ecosystem services should be discounted at a rate that is significantly lower than the one for manufactured consumption goods, with the difference between the two discount rates ranging from 0.5 ± 0.3 %-points (Brazil) to 2.1 ± 0.9 %-points (India). The difference is larger in less developed countries (India, Namibia) and smaller in more developed countries (Germany, UK). On global average over all ecosystem services studied, we found that ecosystem services should be discounted at a rate that is 0.9 ± 0.3 %-points lower than the one for manufactured consumption goods.

From the discussion of systematic errors in our analysis (cf. Sect. 5) it is apparent that we have most likely underestimated the difference in discount rates. Hence, our analysis provides a methodologically conservative estimate of these numbers. This suggests to actually use a discount rate for ecosystem services that is even lower (and possibly much lower) than the numbers reported here.

Our results support and substantiate the suggestion that public cost-benefit-analyses of projects with economic and ecological impacts should use country-specific dual discount rates—one for manufactured consumption goods and one for ecosystem services. While this is already (or decided to become) good-practice in some countries, e.g. in France and Norway, our analysis suggests to generally adopt this practice in all countries.

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 manufactured 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 (TEEB 2011: Sect. 3.5). 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), TEEB (2010) or the UK National Ecosystem Assessment (2011a, b) are the first steps in this direction, and they point the way.

References

Boyd J, Banzhaf S (2007) What are ecosystem services? The need for standardized environmental accounting units. Ecol Econ 63(2–3):616–626

Broberg T (2010) Income treatment effects in contingent valuation: the case of the Swedish predator policy. Environ Resour Econ 46(1):1–17

CIA—Central Intelligence Agency (2011) CIA World Factbook. Appendix B: international organizations and groups. https://www.cia.gov/library/publications/the-world-factbook/appendix/appendix-b.html, last access 2011–07–17

CBD—United Nations Convention on Biological Diversity (2006) COP 8 Decision VIII/15. http://www.cbd.int/decision/cop/?id=11029, last access 2011–07–01

Chiabai A, Travisi C, Markandya A, Ding H, Nunes P (2011) Economic assessment of forest ecosystem services losses: cost of policy inaction. Environ Resour Econ 50(3):405–445

DESTATIS—German Federal Statistical Office (2011) Genesis-Online Datenbank—Forstbetriebe, Waldfläche: Deutschland, Jahre. https://www-genesis.destatis.de/genesis/online/data;jsessionid=9278DFB5F2A71B826D5E291405728DE2.tomcat_GO_2_2?operation=abruftabelleBearbeiten&levelindex=2&levelid=1327832548017&auswahloperation=abruftabelleAuspraegungAuswaehlen&auswahlverzeichnis=ordnungsstruktur&auswahlziel=werteabruf&selectionname=41100-0010&auswahltext=&werteabruf=Werteabruf

DESTATIS—German Federal Statistical Office (2010) Nachhaltige Entwicklung in Deutschland, Indikatorenbericht 2010, Wiesbaden, Indicator: Artenvielfalt und Landschaftsqualität. https://www-genesis.destatis.de/genesis/online/data;jsessionid=01CE277E5B42AB914D462DEC2B818A8Dtomcat_GO_2_1?operation=abruftabelleBearbeiten&levelindex=2&levelid=1327834934034&auswahloperation=abruftabelleAuspraegungAuswaehlen&auswahlverzeichnis=ordnungsstruktur&auswahlziel=werteabruf&selectionname=91111-0001&auswahltext=&werteabruf=Werteabruf

Ebert U (2003) Environmental goods and the distribution of income. Environ Resour Econ 25(4):435–459

Echazu L, Nocetti D, Smith WT (2012) A new look into the determinants of the ecological discount rate: disentangling social preferences. B.E. J Econ Anal Policy 12(1):1–44

FAO—Food and Agriculture Organization of the United Nations, Statistics Division (2011a) AQUASTAT review of water resources statistics by country. http://www.fao.org/nr/water/aquastat/water_res/index.stm, last access 2011–05–05

FAO—Food and Agriculture Organization of the United Nations, Statistics Division (2011b) FAOSTAT Forestry-ForeSSTAT-Roundwood(Total) for Brazil, Germany, India, Namibia, United Kingdom, World (Total). http://faostat.fao.org/site/626/DesktopDefault.aspx?PageID=626#ancor, last access 2011–05–16

FAO—Food and Agriculture Organization of the United Nations, Statistics Division (2011c) FAOSTAT production-crops for Brazil, Germany, India, Namibia, United Kingdom, World (Total). http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor, last access 2011–07–22

FAO—Food and Agriculture Organization of the United Nations, Statistics Division (2011d) FAOSTAT production-live animals-beehives for Brazil, Germany, India, Namibia, United Kingdom, World (Total). http://faostat.fao.org/site/573/DesktopDefault.aspx?PageID=573#ancor

FAO—Food and Agriculture Organization of the United Nations, Statistics Division (2011e) FAOSTAT production-livestock primary for Brazil, Germany, India, Namibia, United Kingdom, World (Total). http://faostat.fao.org/site/569/DesktopDefault.aspx?PageID=569#ancor, last access 2011–07-22

FAO—Food and Agriculture Organization of the United Nations, Statistics Division (2011f) FAOSTAT Resources-ResourceStat-Land-Forest Area for Brazil, Germany, India, Namibia, United Kingdom, World (Total). http://faostat.fao.org/site/377/DesktopDefault.aspx?PageID=377#ancor

FAO—Food and Agriculture Organization of the United Nations, Statistics and Information Service of the Fisheries and Aquaculture Department (2011g) Total fishery production 1950–2009. FishStat Plus—Universal software for fishery statistical time series. http://www.fao.org/fishery/statistics/software/fishstat/en, last access 2011–08-12

Gerlagh R, van der Zwaan BCC (2002) Long-term substitutability between environmental and man-made goods. J Environ Econ Manag 44:329–345

Gollier C (2010) Ecological discounting. J Econ Theory 145:812–829

Guéant O, Guesnerie R, Lasry J-M (2012) Ecological intuition versus economic "reason". J Public Econ Theory 14(2):245–272

Guesnerie R (2004) Calcul économique et développement durable. Revue économique 55(3):363–382

Haines-Young R, Potschin M (2012) Common International Classification of Ecosystem Services (CICES): Consultation on Version 4, August-December 2012 (Report to the European Environment Agency, revised January 2013). http://www.cices.eu

Hammitt J, Liu J-T, Liu J-L (2001) Contingent valuation of a Taiwanese wetland. Environ Develop Econ 6:259–268

Hasselmann K, Hasselmann S, Giering R, Ocana V, von Storch H (1997) Sensitivity study of optimal CO_2 emission paths using a simplified structural integrated assessment model. Clim Change 37:345–386

Heal GM (1999) Valuing the future. Columbia University Press, New York

Heal GM (2009) The economics of climate change: a post-Stern perspective. Clim Change 96:275–297

Hoel M, Sterner T (2007) Discounting and relative prices. Clim Change 84:265–280

Hökby S, Söderqvist T (2003) Elasticities of demand and willingness to pay for environmental services in Sweden. Environ Resour Econ 26(3):361–383

Hoffmann M, Hilton-Taylor C et al (2010) The impact of conservation on the status of the world's vertebrates. Science 330:1503–1509

Horowitz JK (2002) Preferences in the future. Environ Resour Econ 21:241–259

Horowitz JK, McConnell KE (2003) Willingness to accept, willingness to pay and the income effect. J Econ Behav Organ 51:537–545

Jacobsen J, Hanley N (2009) Are there income effects on global willingness to pay for biodiversity conservation? Environ Resour Econ 43(2):137–160

Khan H (2009) Willingness to pay and demand elasticities for two national parks: empirical evidence from two surveys in Pakistan. Environ Develop Sustain 11(2):293–305

Kögel T (2009) On the relation between discounting of climate change and Edgeworth-Pareto substitutability. Economics. The Open-Access, Open-Assessment E-Journal 3(2009–27):1–12 (Version 2 - January 3, 2011)

Kovenock D, Sadka E (1981) Progression under the benefit approach to the theory of taxation. Econ Lett 8:95–99

Kriström B, Riera P (1996) Is the income elasticity of environmental improvements less than one? Environ Resour Econ 7:45–55

Liu S, Stern DI (2008) A meta-analysis of contingent valuation studies in coastal and bear-shore marine ecosystems. CSIRO Working Paper Series 2008–15

Malinvaud E (1953) Capital accumulation and the efficient allocation of resources. Econometrica 21(2):233–268

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being. World Resources Institute, Washington

Neumayer E (1999) Global warming: discounting is not the issue, but substitutability is. Energy Policy 27:33–43

Plambeck EL, Hope C, Anderson J (1997) The PAGE95 model: integrating the science and economics of global warming. Energy Econ 19:77–101

Price C (1993) Time, discounting and value. Blackwell, Oxford

Price C (2003) Diminishing marginal utility: the respectable case for discounting? Int J Sustain Develop 6:117–132

Ramsey FP (1928) A mathematical theory of saving. Econ J 38:543–559

Ready RC, Malzubris J, Senkane S (2002) The relationship between environmental values and income in a transition economy: surface water quality in Latvia. Environ Develop Econ 7(1):147–156

Scandizzo PL, Ventura M (2008) Contingent valuation of natural resources: a case study for Sicily, ISAE Working Paper No. 91

Schläpfer F (2006) Survey protocol and income effects in the contingent valuation of public goods: a meta-analysis. Ecol Econ 57(3):415–429

Schläpfer F, Hanley N (2006) Contingent valuation and collective choice. KYKLOS 59(1):115–135

Söderqvist T, Scharin H (2000) The regional willingness to pay for a reduced eutrophication in the Stockholm archipelago, Beijer Discussion Paper No. 128

Sterner T, Persson UM (2008) An even sterner report: introducing relative prices into the discounting debate. Rev Environ Econ Policy 2(1):61–72

TEEB—The Economics of Ecosystems and Biodiversity (2010) Mainstreaming the economics of nature: a synthesis of the approach, conclusions and recommendations of TEEB. http://www.teebweb.org

TEEB—The Economics of Ecosystems and Biodiversity (2011) The economics of ecosystems and biodiversity in national and international policy-making. In: Ten Brink P (ed) London and Washington DC: Earthscan

Tol RSJ (2003) On dual-rate discounting. Econ Model 21:95–98

Traeger CP (2011) Sustainability, limited substitutability, and non-constant social discount rates. J Environ Econ Manag 62:215–228

UK Department of Environment, Food and Rural Affairs DERFA (2011a) UK biodiversity indicators in your pocket 2011. Measuring progress towards halting biodiversity loss, London. Indicator: 1a. species—wild birds. http://jncc.defra.gov.uk/page-4235

UK Department of Environment, Food and Rural Affairs DERFA (2011b) UK biodiversity indicators in your pocket 2011. Measuring progress towards halting biodiversity loss, London. Indicator: 1b. species—butterflies. http://jncc.defra.gov.uk/page-4236

UK National Ecosystem Assessment (2011a) The UK national ecosystem assessment—synthesis of key findings, UNEP-WCMC, Cambridge. http://uknea.unep-wcmc.org/

UK National Ecosystem Assessment (2011b) The UK national ecosystem assessment—technical report, UNEP-WCMC, Cambridge. http://uknea.unep-wcmc.org/

United Nations, Department of Economic and Social Affairs, Population Division (2011) World Population Prospects. The 2010 Revision, CD-ROM edition

UNDP—United Nations Development Programme (2011) Human development report 2011, Palgrave Macmillan, New York. http://hdr.undp.org/en

UNEP—United Nations Environment Programme (2011) Environmental data explorer, dataset: water resources—total renewable (actual). http://geodata.grid.unep.ch/

United Nations et al. (2012) System of environmental-economic accounting: central framework 2012 (white-cover edition), New York. http://unstats.un.org/unsd/envaccounting/seea.asp

Wang H, Shi Y, Kim Y, Kamata T (2013) Valuing water quality improvement in China. A case study of Lake Puzhehei in Yunnan Province. Ecol Econ 94:56–65

Weikard HP, Zhu X (2005) Discounting and environmental quality: when should dual rates be used? Econ Model 22:868–878

World Bank (2011a) Data-indicators-land area (sq. km) available at http://data.worldbank.org/indicator/AG.LND.TOTL.K2

World Bank (2011b) Data-indicators-roads, total network (km). http://data.worldbank.org/indicator/IS.ROD.TOTL.KM

World Bank (2011c) Metadata agriculture, value added (% of GDP). http://databank.worldbank.org/ddp/viewSourceNotes?REQUEST_TYPE=802&DIMENSION_AXIS=ROW&SELTECTED_DIMENSION=WDI_Series&PARENT_MEMBER_INFO, last access 2011–07-25

World Bank (2011d) Metadata GDP, PPP (constant 2005 international US$). http://databank.worldbank.org/ddp/viewSourceNotes?REQUEST_TYPE=802&DIMENSION_AXIS=ROW&SELTECTED_DIMENSION=WDI_Series&PARENT_MEMBER_INFO, last access 2011–05-18

WWF—World Wildlife Fund for Nature and Zoological Society of London (2010) Living planet report 2010. Gland. Excel file for figures on p. 20 and p. 77 provided by the report's co-author Jonathan Loh by email on June 1, 2011

Yang Z (2003) Dual-rate discounting in dynamic economic-environmental modelling. Econ Model 20:941–957

Yu X, Abler D (2010) Incorporating zero and missing responses into CVM with open-ended bidding: willingness to pay for blue skies in Beijing. Environ Develop Econ 15:535–556