

Baumgärtner, Stefan; Klein, Alexandra M.; Thiel, Denise; Winkler, Klara

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## Ramsey discounting of ecosystem services

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Stefan Baumgärtner, Alexandra M. Klein,  
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# Ramsey discounting of ecosystem services

STEFAN BAUMGÄRTNER<sup>a,\*</sup> ALEXANDRA M. KLEIN<sup>a,b</sup>, DENISE THIEL<sup>a,c</sup>  
and KLARA WINKLER<sup>a,d</sup>

<sup>a</sup> Leuphana University of Lüneburg, Germany

<sup>b</sup> University of Freiburg, Germany

<sup>c</sup> Lund University, Sweden

<sup>d</sup> University of Life Sciences, Vienna, Austria

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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  $0.9 \pm 0.3$  %-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.

**JEL-Classification:** H43, Q28, Q51, Q57

**Keywords:** discounting, ecosystem services, (de)growth, heterogeneous consumption, Ramsey model, substitution

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\*Corresponding author: Sustainability Economics Group, Leuphana University of Lüneburg, P.O. Box 2440, D-21314 Lüneburg, Germany. Phone: +49.4131.677-2600, fax: +49.4131.677-1381, email: baumgaertner@uni.leuphana.de, url: <http://www.leuphana.de>.

# 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 this opposite development in public cost-benefit analyses of projects with economic and ecological impacts, it has been suggested, based on a two-goods extension of Ramsey's (1928) growth model, to apply dual discount rates for manufactured 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).<sup>1</sup>

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.

The sole empirical estimate up to now of how the “ecological discount rate” should

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

differ from the consumption discount rate has been provided by Gollier (2010: Sec. 6). His empirical analysis is restricted in two ways.<sup>2</sup> 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 closed 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 between manufactured consumption goods and ecosystem services, and constant intertemporal elasticity of substitution. For an empirical estimate of the (de)growth of ecosystem services, we analyzed time-series data for the period 1950–2010 on 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  $3.6 \pm 1.4$  %-points lower than the one for manufactured consumption goods (cultural services in India) and  $0.8 \pm 0.3$  %-points higher than the one for manufactured consumption goods (provisioning services in Germany). In all five countries studied, aggregate ecosys-

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<sup>2</sup>The main motivation and achievement of his analysis are theoretical, anyway. The empirical analysis in Section 6 of his paper only serves as a numerical illustration of the theoretical results.

tem 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  $0.5 \pm 0.3$  %-points (Brazil) to  $2.1 \pm 0.9$  %-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  $0.9 \pm 0.3$  %-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, constant elasticity of substitution (CES) between them in instantaneous consumption, and constant intertemporal elasticity of substitution (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 Section 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.<sup>3</sup>

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

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

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

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<sup>3</sup>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).

$U_C$  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):

$$r_C = \rho + \epsilon_{CC} g_C + \epsilon_{CE} g_E , \quad (2)$$

$$r_E = \rho + \epsilon_{EE} g_E + \epsilon_{EC} g_C , \quad (3)$$

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

$$g_C := \frac{dC_t/dt}{C_t} , \quad (4)$$

$$g_E := \frac{dE_t/dt}{E_t} , \quad (5)$$

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

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

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

$$\epsilon_{CE} := -\frac{U_{CE}(C_t, E_t) E_t}{U_C(C_t, E_t)} \begin{matrix} \geq \\ < \end{matrix} 0 , \quad (8)$$

$$\epsilon_{EC} := -\frac{U_{EC}(C_t, E_t) C_t}{U_E(C_t, E_t)} \begin{matrix} \geq \\ < \end{matrix} 0 . \quad (9)$$

The own elasticities,  $\epsilon_{CC}$  and  $\epsilon_{EE}$ , 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,  $\epsilon_{CE}$  and  $\epsilon_{EC}$  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 assumed that the instantaneous utility function  $U(\cdot, \cdot)$  is characterized by a constant elasticity of substitution (CES) between the manufactured good and the ecosystem service in instantaneous aggregate consumption, and a constant intertemporal elasticity of substitution (CIES) of instantaneous aggregate consumption:

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

with  $0 < \alpha < 1$ ,  $0 < \sigma < +\infty$ ,  $\eta \geq 0$ ,

where  $\alpha$  is the relative weight of manufactured-good consumption in instantaneous aggregate consumption,  $\sigma$  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. For  $\sigma > 1$  the manufactured good and the ecosystem service are substitutes in instantaneous consumption and the cross elasticities  $\epsilon_{CE}$  and  $\epsilon_{EC}$  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 (Hoel and Sterner 2007: Equ. 12, Traeger 2011: Equ. 7)

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

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,  $\sigma \rightarrow +\infty$ , 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,  $\Delta r$ , 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,  $\rho$ , 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,  $\Delta r$  (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.

Likewise, while the (inverse) intertemporal elasticity of substitution,  $\eta$ , 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,  $\Delta r$  (Equation 11). The reason is that – like the rate of pure time preference – 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 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 – 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.<sup>4</sup> 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 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: Sec. 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

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<sup>4</sup>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	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 <sup>3</sup> per year
water	y	renewable water resources	kilometer <sup>3</sup> 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 km) divided by the the country’s land area (in kilometer<sup>2</sup>).

(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 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)<sup>5</sup>. 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)<sup>6</sup>, forest area, the Living-Planet-Index and a biodiversity indicator (with the Red-List-Index 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. Section 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

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<sup>5</sup>Established and well documented national biodiversity indicators exist for Germany and the UK.

<sup>6</sup>Road density is calculated as the total length of a country’s road network divided by the the country’s land area

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 10 years. 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 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 are 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 Section 3.5).

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

### **3.4 Data on manufactured goods and services**

Production of manufactured and market-traded consumption goods was measured as per-capita gross domestic product (GDP) in units of 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 came from the *World Development Indicators* database (World Bank 2011d). From these data, we subtracted the agricultural share of GDP (reported by World Bank 2011c), to avoid double counting of market-traded provisioning ecosystem services. For, all agricultural products were taken into account explicitly in our analysis as (provisioning) ecosystem services. The numbers 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 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 and the time period of the current trend was identified by eye’s inspection. Next, an exponential function was fitted (using Microsoft Excel) to the data over the time period thus identified, 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 was estimated.

To estimate the error in the growth rate thus measured, the start year and the end year of the fit were varied and, again, a constant growth rate was obtained for each varied period. Thus, maximal and minimal growth rates were identified. The average of the two extremes was used as the best estimate of the annual growth rate for the following calculation. Its standard deviation was 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 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 at each level, 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 (Section 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.<sup>7</sup>

### 3.7 Data on substitutability

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

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<sup>7</sup>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.

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  $0.38 \pm 0.14$ . 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 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.

### 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  $\Delta x$ . 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:

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

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  $\Delta r$  according to Equation (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,

$$\Delta(g_C - g_E) = |\Delta g_C| + |\Delta g_E|, \quad (13)$$

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

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

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.

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

## 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  $\Delta r$ .

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. Table 5 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 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

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 $\pm 0.06$	0.15 $\pm 0.03$	0.59 $\pm 0.02$	1.64 $\pm 0.13$	-2.10 $\pm 0.12$	0.45 $\pm 0.02$
growth rate of livestock production	2.01 $\pm 0.03$	0.15 $\pm 0.05$	1.92 $\pm 0.06$	-2.05 $\pm 0.07$	-0.70 $\pm 0.02$	0.72 $\pm 0.03$
growth rate of total fishery production	3.09 $\pm 0.03$	-3.38 $\pm 0.04$	2.02 $\pm 0.01$	-4.63 $\pm 0.22$	-0.84 $\pm 0.02$	1.51 $\pm 0.02$
range of food prov.	1.99 $\pm 0.06$	-3.38 $\pm 0.04$	0.59 $\pm 0.02$	-4.63 $\pm 0.22$	-2.10 $\pm 0.12$	0.45 $\pm 0.02$
services growth rate	... 3.09 $\pm 0.03$	... 0.15 $\pm 0.05$	... 2.02 $\pm 0.01$	... 1.64 $\pm 0.13$	... -0.70 $\pm 0.02$	... 1.51 $\pm 0.02$
mean food prov. services growth rate	2.36 $\pm 0.36$	-1.03 $\pm 1.18$	1.51 $\pm 0.46$	-1.68 $\pm 1.82$	-1.21 $\pm 0.45$	0.89 $\pm 0.32$

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-categories 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

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

	Brazil	Germany	India	Namibia	UK	World
range of food prov.	1.99 ±0.06	-3.38 ±0.04	0.59 ±0.02	-4.63 ±0.22	-2.10 ±0.12	0.45 ±0.02
services growth rate	...	...	...	...	...	...
mean food prov.	3.09 ±0.03	0.15 ±0.05	2.02 ±0.01	1.64 ±0.13	-0.70 ±0.02	1.51 ±0.02
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	0.68 ±0.06	3.90 ±0.14	-0.95 ±0.02	-1.56 ±0.02	2.41 ±0.03	-1.03 ±0.01
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	-2.00 ±0.02	-3.38 ±0.04	-2.10 ±0.00	-4.63 ±0.22	-2.10 ±0.12	-1.25 ±0.01
services growth rate	...	...	...	...	...	...
mean provisioning	3.09 ±0.03	3.90 ±0.14	2.02 ±0.01	1.64 ±0.13	2.41 ±0.03	1.51 ±0.02
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.

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 ...
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).

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

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 ...
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.

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 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 10 puts all pieces together and shows the calculation of  $\Delta r$  according to Equation (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  $\Delta r$ , the uncertainties in-

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

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

Table 10: Calculation of  $\Delta r$ .

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

crease. Nevertheless, in all countries the mean value of  $\Delta r$  is significantly larger than zero. It ranges from 0.5 %-points in Brazil to 2.1 %-points in India. At the global scale,  $\Delta r$  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 is excellent and easily available, 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,  $g_E$ , (that is: underestimated the absolute amount of negative growth of ecosystem services) and, hence, underestimated the value of  $\Delta r$ .

Second, our estimate of the elasticity of substitution,  $\sigma$ , 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  $\sigma$  and, hence, underestimated the value of  $\Delta r$ .

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 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: Sec. 6.1) shows (for Cobb-Douglas utility function, though) that the difference in discount rates,  $\Delta r$  (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. If the degrees of risk aversion on both goods are equal, this additional term to  $\Delta r$  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,  $\Delta r$ , 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  $\Delta r$ . Neglecting uncertainty (due to lack of data), we have therefore probably underestimated the value of  $\Delta r$ .

Considering these three biases, the systematic errors thus induced into our analysis all go in the same direction: we have most likely underestimated the difference  $\Delta r$  in discount rates. Although we cannot tell how large this error is, it seems safe to say that our estimate of  $\Delta r$  is a methodologically conservative estimate, and the real value for  $\Delta r$  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  $0.5 \pm 0.3$  %-points (Brazil) to  $2.1 \pm 0.9$  %-points (India). The difference is larger in less developed countries (India, Namibia) and smaller in more developed countries (Germany, UK). On global average over all ecosystem services studied, we found that ecosystem services should be discounted at a rate that is  $0.9 \pm 0.3$  %-points lower than the one for manufactured consumption goods.

From the discussion of systematic errors in our analysis (cf. Section 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: Sec. 3.5). These countries are thus facing a double challenge: while (1) ecosystem ser-

vices 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.

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