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Calculation of Monetary Values of Environmental Impacts from Emissions and Resource Use

The Case of Using the EPS 2015d Impact Assessment Method

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Abstract

Monetary values of environmental impacts from emissions and from use of natural resources help in understanding the environmental significance of human activities. It is however a complicated and time consuming task to determine these values, and the values are easy to uncritically accept without understanding the many ways they may be determined, the many preferences they may represent and the different contexts for which they may be relevant.

This article aims at increasing the usefulness of monetary valuation and decreasing some of its shortcomings by demonstrating a way to model and calculate monetary values of environmental impacts from emissions and use of natural resources, highlight subjective choices that have to be made in modelling and calculations, and discuss how some of them influence the values assessed.

The method we use is based on the principles of the EPS default impact assessment method, which comply with the requirements of the ISO 14044 life cycle assessment standard.

Monetary values for 98 endpoint category indicators are determined, and calculations of characterization factors are demonstrated for CO_2, N_2O, CH_4, and NO_x.

Two methodological choices have proven particularly important for the values obtained. One is the long term perspective and intergenerational equity. The other is the approach to uncertainty. Both is important for what is included in the assessments and to what extent.

Keywords: eco-design, impact assessment, life cycle assessment, monetary valuation, natural capital, social cost of carbon, weighting

1. Introduction

Monetary values of environmental impacts from emissions and from use of natural resources help in understanding the significance of environmental consequences of human activities. One reason for this is that economy has a central role in guiding choices in life. Another reason is that sustainability, as defined by UN through the Brundtland commission, focus on human well-being and freedom from poverty, which is largely an economic issue. There are however drawbacks in using monetary values. One is that it is a complicated and time consuming task to determine monetary values of emissions and use of natural resources, and there are few examples of ready-made comprehensive assessments of emissions and natural resources that can be used. Another shortcoming is that monetary values are easy to uncritically accept without understanding the many ways they may be determined, the many preferences they may represent, and the different contexts for which they may be relevant. A third shortcoming is that monetary valuation imply that environmental assets are interchangeable among themselves and with other assets.

Monetary values have been used for weighting in several LCA methods: EPS 2000d (Steen, 1999), Eco-cost (Vogtländer et al, 2001) Ecotax 2002 (Finnveden, Eldh & Johansson, 2006), Stepwise 2006 (Weidema, 2009) and Ecovalue08 (Alroth & Finnveden, 2011). Monetary values for environmental impacts has since long been used within cost-benefit analysis (CBA). Such values may also be used in LCA, e.g. monetary values from recent European projects like ExternE, NEEDS and CASES (CASES 2008). In table 1, some features of these methods are summarized.

There are many challenges when assessing monetary values of environmental impacts. Some has to do with choice of relevant system boundaries. System boundaries exist for the technical system (specifying which flows and activities that is valued) as well as for the environmental system (specifying which impacts that is valued, where and when) and the economic system (specifying whose values that are assessed, and in which context).

Other challenges have to do with complexity and assessment resources. It is a gigantic challenge to model all environmental impacts from all emissions and resources to endpoints where they can be valued with a reasonable repeatability. And even if models are sophisticated and accurate, it may be impossible for a user to understand how they are made, and thus understand what the resulting values represent. Knowledge also changes with time and assessments need to be updated.

Table 1. Some features of methods used in LCA weighting based on monetary valuation

Method name	***Safeguard subjects*** and **Indicators being valued**	**Valuation method**
EPS 2000d	*Human health*: Life expectancy, morbidity, nuisance; *Bio-productivity*: crop, fish&meat, wood; *Biodiversity*: threat contribution; *Abiotic resources*: water, fossil fuels, metal ores, minerals	Market values
Eco-cost	*Human health*: fine dust, summer smog, carcinogens; *Ecosystems*: eutrophication, eco-toxicity, acidification, GWP100; *Resource depletion*: fossil fuels, waste, land use, water scarcity, abiotic resource depletion	Prevention costs
Ecotax 2002	Abiotic fossil resources, biotic energy resources, Global warming, Depletion of stratospheric ozone, Photochemical oxidation, Acidification, Eutrophication, Fresh water aquatic ecotoxicity, Marine aquatic ecotoxicity, Terrestrial ecotoxicity, Terrestrial ecotoxicity	Swedish tax
Stepwise 2006	*Human well-being*, *ecosystems*, *resource productivity*	Diverse
Eco-value08	Acidification, Eutrophication, Forming of tropospheric ozone, Global warming, Human toxicity	Contingent valuation and market prices
ExternE, NEEDS and CASES	*Human health, building materials, crops, biodiversity, climate*	WTP, prevention costs, market values

This article aims at increasing the usefulness of monetary valuation, and decreasing some of its shortcomings by 1) updating existing EPS models to calculate monetary values of environmental impacts from emissions and use of natural resources, 2) highlight subjective choices that have to be made in modelling and calculations, and 3) discuss how some of them influence the monetary values assessed.

Much of the references data comes from IPCC's fifth assessment reports from working group I and II (IPCC, 2013, and IPCC 2014). For simplicity the data sources are referenced directly in the text e.g. IPCC AR5 WGI Table 8.SM.19.

2. Method

2.1 Description of the EPS Impact Assessment Method

The EPS default impact assessment method was originally developed as a part of a systematic approach to guide designers and product developers in choices between design options. This systematic approach was named the EPS system. It is based on LCA methodology, and follows the ISO 14044 Standard (Steen 1999a). The EPS environmental impact assessment method is a part of the EPS system and its preceding default impact assessment database was published 1999 (Steen, 1999b). The version described here has the reference year 2015. EPS is an acronym for "Environmental Priority Strategies in product design.

The EPS system was developed in a top-down manner, aiming at informing the product developer of the environmental damage cost he or she would cause by a particular product design. As assessment of sustainability

– to a very large extent- is an ethical issue, there is no single true value, but there are more or less meaningful values. To a product developer, or other decision maker, it is meaningful to know what people like he or she would be willing to pay, to avoid the environmental damages his or her decision would cause, if the damages impacted on him/her. The product developer and stakeholders are not supposed to be willing to pay more than it takes, so market values or estimated market values are considered as relevant measures for the damage cost.

In the EPS default impact assessment method, global average damage costs are estimated for emissions and resources, and the values of an average OECD inhabitant is used. Impacts from emissions and use of resources, which cause significant changes in any of the safeguard subjects: eco-system services, access to water, abiotic resources, human health and biodiversity, are in focus. The safeguard subjects and their state indicators are chosen to represent the sustainability aspect of the environment and human health.

Damage costs for an emission or resource are determined as the sum of damage costs caused by the emission or resource on the safeguard subject's state indicators via different mechanisms (pathways). Costs are determined as the product of characterization factors and monetary values of state indicators. Characterization factors are determined by estimating the extent of an impact and multiplying with the contribution from 1 unit of the emission or resource to the extent. Linear dose-response models are used. Non linearity is treated as uncertainty.

An impact is determined as an integrated effect over the time and space, where it occurs. As the value described is the one of a present OECD-inhabitant, having the impacts on her/himself, 0% discounting of future effects is used. There are two more reasons for using 0 % discounting. One is that a very large part of the impact values is caused by effects on human health and productivity, and that the valuation of human life and health is likely to follow economic growth (or decline). A second reason is that a management tool that is supposed to guide towards sustainable growth, would lose some of its power if it assumed that growth would occur anyway. The use of the same values for all affected persons may be seen as a kind of equity weighing. All data are given as a best estimate and an uncertainty factor, mostly representing a standard deviation in a log-normal distribution.

Values for state indicators are determined via market values or estimated market values. For some ecosystem services, like crop production, direct market values are available. For others, like access to water and abiotic resources, restoration costs are used as an approximation, as a market price in the future would at least be equal to the production cost for a similar good. For human health DALY (Disability Adjusted Life Years) values are used and for biodiversity prevention costs to reach international targets.

Uncertainty is a part of reality in monetary valuation of emissions and use of natural resources. The estimation of uncertainty is a particular problem, for several reasons.

1) It is dependent on the product system analyzed. If all unit processes are located on the same spot, and we use a global average, the uncertainty is larger than if the unit processes are scattered all over the world.
2) There is seldom sufficient statistics to allow an objective calculation of variations.
3) Some of the most severe impacts on sustainability have to do with long term issues, and the uncertainty about the future is more than what can be described by uncertainty distributions
4) Uncertainty distributions are not easily expressed by continuous mathematical expressions

However, omitting uncertainty from an LCA could be misleading. Therefore, it is still used to characterize a default estimate. An average size of product systems is assumed, and as much information on uncertainty that can be found is used to estimate the magnitude of the uncertainty. In Steen (2015a and 2015b) uncertainty estimates are given and the reasons for uncertainty estimates are given as notes. In this paper uncertainty data are only given for monetary values of state indicators.

When communicating damage costs, the unit ELU (Environmental Load Units) is often used in the EPS approach instead of EUR in order to create a moment of thought before just adding it up to ordinary currency. After all, there are many ways of estimating economic values of nonmarket issues, and it may be worth considering exchange rates before crossing system boundaries.

2.2 The Method Used for the Research Presented in This Article

Updating of monetary values of emissions and use of resources were made by the EPS default impact assessment method. The main method was web searches on scientific literature and official data. Priority was given to those data that was contributing most to global environmental damage cost estimates in the preceding version of EPS (Steen 1999), i.e. greenhouse gases, ores and fossil minerals.

Updating was made both with respect to which impacts that was included, and with respects to the models determining the extent of an impact from a unit of emission or resources use.

Subjective choices were identified using the ISO 14040 and 14044 standards and the consequence of alternative choices investigated using sensitivity analyses for the total global environmental impact values, .i.e. the values obtained when multiplying damage cost for unit emissions or resources with the global flows.

3. Results

3.1 Monetary Values of State Indicators

The state indicators for *ecosystem services* and *access to water* describe the *capacity* of environments to produce crop, fruit & vegetables, wood, fish & meat and water of different qualities, *not the production per se*. Their values are estimated from market prices (table 2). Market prices for crops are reported by FAO (2013). As much of the impacts are caused by climate change and expected to double within the next century compared to market prices around 2000 (Porter et al., 2014) and different crops sell for different prices, uncertainty factor is estimated to 2. Prices and variation in prices for fruit & vegetables and for fish&meat are also reported by FAO (2013). The price and cost of drinking water varies a lot between different countries and includes quality adjustments at source as well as distributions costs. OECD (2013a) reports prices excluding taxes and sewage treatment. European Environmental Agency (EAA 2009) reports that the cost of irrigation water is about the half of that of drinking water.

Table 2. State indicator values for the safeguard subjects *ecosystem services* and *access to water*

State indicator	Indicator unit	Monetary value (€/ indicator unit)	Reference	Uncertainty factor
Crop growth capacity	kg	0.22	FAO 2013	2
Fruit & vegetables prod. capacity	kg	0.39	FAO 2013	2
Wood growth capacity	kg	0.04	Swedish Statistical Yearbooks of Forestry (2014)	1.4
Fish & meat production capacity	kg	2.1	FAO 2013	2.1
Drinking water	kg	0.002	OECD 2013	2
Irrigation water	kg	0.001	OECD 2013, EEA (2009)	2

The values of state indicators for the safeguard subject abiotic resources are determined as the restoration or replacement cost of the resource. Even if abiotic resources often are regarded as finite, they may be restored or replaced by technical processes.

Fossil oil may be replaced by biomass transformed to oil-like hydrocarbons in a Fisher-Tropsch process, which is a well-known process as well as its cost (Vliet et al., 2009). The uncertainty is estimate do be comparatively low, as there is a long experience of the process.

Coal in fossil coal may be replaced by charcoal made from wood at a cost of 0.161 €/kg coal. The cost is mainly cost for wood and for flash pyrolysis (Norgate and Langberg, 2009). Besides charcoal, char and volatile gases are produced. Thus, emissions of CO and methane and their external costs have to be distributed between the charcoal and the byproducts. An energy balance on the equilibrium product mixture from the model compound cellulose at 400 °C and 1 MPa indicates that the carbon product retains 52.2% of the higher heating value (HHV) of the cellulose (17.4 MJ/kg), and 36.2% is captured by the gas products (primarily methane). The remaining 2.0 MJ/kg is released as heat by the exothermic pyrolysis reaction. (Antal and Grønli 2003). Here 52.2/(52.2+36.2) = 59% of the wood feed is allocated to Charcoal.

Natural gas may be replaced by biogas. The process is commercial and costs are known. Production cost is reported by United States Department of Agriculture (2007).

Metal ores and other element concentrates may be restored by crushing, grinding, and leaching ordinary rock minerals and precipitate metals or other elements from the leachate (Steen & Borg, 2002). Costs are approximately inversely proportional to the concentration. Calculations of costs are made by Steen and Borg (2002) and updated in the EPS 2015d version with new data on the abundance of element in earth's upper crust, (UNEP, 2011). The uncertainty is estimated to a factor of 2.2 for metals where experiments were carried out and to 3 for those where assumptions had to be made for extraction efficiency. The uncertainty is high as production processes of these types do not exist today. Some elements, like Na, I and Br are already today extracted from a sustainable source (sea water) and will not cause any costs of restoration. Replacement costs for B, Li and K through evaporation of sea water is highly speculative and uncertainty is set to a factor of 10. Estimated values for state indicators of abiotic resources are shown in table 3.

Table 3. State indicator values for the safeguard subject abiotic resources

State indicator	Indicator unit	Monetary value (€/ indicator unit)	Uncer-tainty factor	State indicator	Indicator unit	Monetary value (€/ indicator unit)	Uncer-tainty factor
Fossil oil	kg	0.470	1.4	Lu	kg of element	1.14E+04	3
Fossil coal	kg	0.161	2	Mg salt	kg of element	0.00E+00	1
Natural gas	kg	0.276	2	Mn ore	kg of element	4.92E+00	3
Ag ore	kg of element	7.28E+04	2.2	Mo ore	kg of element	2.43E+03	2.2
Al ore	kg of element	3.47E-01	2	Na salt	kg of element	0	1
As ore	kg of element	2.43E+03	2.2	Nb ore	kg of element	3.03E+02	3
Au ore	kg of element	2.02E+06	3	Ni ore	kg of element	1.07E+02	3
Borates	kg of element	5.00E-02	10	Nd ore	kg of element	1.40E+02	3
Ba mineral	kg of element	6.61E+00	3	Os ore	kg of element	7.28E+07	3
Be mineral	kg of element	1.21E+03	3	P mineral	kg of element	5.20E+00	3
Bi ore	kg of element	2.80E+04	2.2	Pb ore	kg of element	3.92E+02	2.2
Br salt	kg of element	0.00E+00	1	Pd ore	kg of element	6.86E+06	3
Cd ore	kg of element	7.05E+04	2.2	Pr ore	kg of element	5.12E+02	3
Ce ore	kg of element	5.68E+01	3	Pt ore	kg of element	6.06E+06	3
Cl salt	kg of element	0.00E+00	1	Rb ore	kg of element	3.31E+01	3
Co ore	kg of element	1.79E+02	3	Re ore	kg of element	9.10E+06	3
Cr ore	kg of element	5.95E+01	3	Rh ore	kg of element	2.02E+08	3
Ce ore	kg of element	5.68E+01	3	Ru ore	kg of element	1.21E+08	3
Cu ore	kg of element	9.09E+01	3	S	kg of element	1.00E-01	5
Dy ore	kg of element	1.04E+03	3	Sb ore	kg of element	1.82E+04	3
Er ore	kg of element	1.58E+03	3	Sc ore	kg of element	2.60E+02	3
Eu ore	kg of element	4.13E+03	3	Se mineral	kg of element	7.28E+01	3

F mineral	kg of element	6.22E+00	3	Sm ore	kg of element	8.08E+02	3
Fe ore	kg of element	7.30E-01	2.2	Sn ore	kg of element	4.82E+02	2.2
Ga ore	kg of element	2.14E+02	3	Sr mineral	kg of element	1.04E+01	3
Gd ore	kg of element	9.57E+02	3	Ta ore	kg of element	3.64E+03	3
Ge ore	kg of element	2.27E+03	3	Tb ore	kg of element	5.68E+03	3
Water	kg of element	0.00E+00	1	Te mineral	kg of element	3.64E+06	3
Hf ore	kg of element	6.27E+02	3	Ti ore	kg of element	8.87E-01	3
Hg ore	kg of element	5.43E+04	2.2	Tl ore	kg of element	1.30E+03	3
Ho ore	kg of element	4.55E+03	3	Tu ore	kg of element	1.10E+04	3
I mineral	kg of element	0	3	U ore	kg of element	3.40E+02	3
I salt	kg of element	0	1	V ore	kg of element	3.40E+01	3
In ore	kg of element	7.28E+04	3	Y ore	kg of element	1.65E+02	3
Ir ore	kg of element	1.65E+08	3	Yb ore	kg of element	1.65E+03	3
K salt	kg of element	1.00E-02	10	Zn ore	kg of element	3.24E+01	2.2
La ore	kg of element	1.21E+02	3	Zr ore	kg of element	1.91E+01	3
Li mineral	kg of element	1.00E-01	3				

The total value of biodiversity has been estimated by McCarthy et al. (2012) who estimated the total Financial Costs of Meeting Global Biodiversity Conservation Targets to be 5.6E+10 €/year. The state indicator for biodiversity is called "NEX", which stands for "normalized extinction of species" and is measured as the share of all red-listed species. If 1% of all red-listed species are threatened by a certain land use type, the NEX value is 0.01.

State indicators for human health represent symptoms relevant for environmental impacts and are selected from the so called DALY system. DALY stands for disability adjusted life years and is an international system mainly used in health care. As we here apply a sustainability perspective in line with the Brundtland commission, basic needs come in focus, and consequently the safeguarding of resources to satisfy basic human needs. Therefore the resource aspect of human health is considered, as is the case for the DALY concept. The DALY factors are taken from WHO (2004) and Salomon et al. (2012). The reference, the value of a year of lost life (YOLL), is determined as the productivity loss for an average employed person in OECD (OECD 2015) adjusted by the share of active years in life and for utilities created outside official work (table 4). A similar figure, 58800 is used for labor productivity, based on the average productivity in the OECD. The average per capita GDP was 46.7 US$ per worked hour. 2012 (OECD 2015). The uncertainty factors are estimated from the variations given for DALY factors and how well the DALY categories represent environmental impacts. For YOLL, the uncertainty represents the spread in values published in the literature.

Table 4. State indicator values for the safeguard subject *human health*

State indicator	Indicator unit	Monetary value (€/ indicator unit)	Uncer-tainty factor
YOLL	personyears	50 000	1.5
Malnutrition	personyears	9550	1.1
Diarrhea	personyears	5250	1.2
Malaria episodes	personyears	5455	1.1
Migration	persons	25 000	5
Gravation of angina pectoris	personyears	3000	2
Cardiovascular disease	personyears	5000	3
Infarcts	personyears	4020	1.3
Asthma cases	personyears	2150	2
COPD severe	personyears	19 150	2
Cancer	personyears	10 000	2
Skin cancer	personyears	2500	1.3
Low vision	personyears	8500	2
Poisoning	personyears	30 000	2
Intellectual disability: mild	personyears	1550	4
Osteoporosis	case	64 000	2
Renal dysfunction	case	32 000	2

3.2 Monetary Values of Emissions

Below, the results are given in tables for different categories of emissions. The total damage cost for an emission is calculated by adding all pathway specific costs.

For spatial reasons it has not been possible to document the impact models for all emission. Only impact models and monetary valuation of emissions of CO2, CH4, N2O and NOx are described. Others are documented in Excel files (Steen 2015a,b) where all calculation are shown and references to numbers given as notes.

3.2.1 Emissions of Carbon Dioxide to Air

The impacts on state indicators from greenhouse gases are modeled using the scenario RCP 6 in IPCCs fifth assessment report (Stocker et al. 2013). The RCP 6 represents the higher radiative forcing scenario of the two middle scenarios. 17 pathway specific characterization factors are determined for CO_2 (table 5).

Table 5. Characterization factors and damage cost estimates for an emission of 1 kg of CO_2

State indicator	Unit	Pathway	Characteri-sation factor	Damage cost (€/ indicator unit)
YOLL	personyears	heat stress	1.35E-07	6.76E-03
YOLL	personyears	cold moderation	-1.28E-09	-6.41E-05
YOLL	personyears	undernutrition	5.00E-07	2.50E-02
YOLL	personyears	flooding	1.18E-08	5.89E-04
YOLL	personyears	diarrheal diseases	2.79E-09	1.40E-04
malnutrition	personyears	food supply	2.39E-06	2.28E-02
working capacity	personyears	heat stress	1.17E-06	6.86E-02
diarrhea	personyears	diarrheal diseases	1.59E-08	8.37E-05
crop	kg	climate change	3.83E-03	8.42E-04
crop	kg	rise of sea level	7.08E-03	1.56E-03

fruit&veg	kg	climate change	1.31E-03	5.09E-04
fish&meat	kg	draught	5.14E-04	1.08E-03
wood	kg	climate change	0.00E+00	0.00E+00
drinking water	kg	climate change	6.28E-02	1.26E-04
irrigation water	kg	climate change	1.26E-01	1.26E-04
migration	persons	climate change	2.27E-07	5.66E-03
NEX	dimensionless	habitat change	2.27E-16	1.27E-05
All				1.35E-1

Reduction of working capacity due to increased temperature is the single impact that contributes most to the damage cost from CO_2. This effect is new in IPCC's fifth assessment reports, and is relatively easy to model. There is a very well-known relation between temperature and humidity and working capacity. Dunne et al. (2013) estimated the decrease in productivity for the global labor force (performing physical labor) to 5% as an average for RCP6. The total workforce with a population of 9 billion is approximately 6*0.65*0.3 = 1.17 billion, where 6 is the population in ages 20-65 years, and 0.65 is the approximate present employment rate in OECD countries (OECD, 2013b) and 0.3 is the share of the work force performing physical labor. 0.3 is estimated from the ILO database ILOSTAT. The total loss of working capacity therefore is 0.05*1.17 = 0.0585 billion person-years/year. Divided with the average CO_2 emission of RCP 6 (38.9 Gton CO_2 equivalents) considering CO_2:s contribution to global warming (88%) and multiplying with the value for a person-year of lost productivity, the damage cost for this type of impact becomes 6.86 E-2 € per kg/CO_2.

The second and third largest single impacts contributing to the damage cost of CO_2 is caused by decreased food supply. IPCC (2013) estimates the decrease in crop production to 1% year and decade until 2100. As an average for the period to 2100, that would be 5%, but as the decline in food production strikes at the most dry and vulnerable regions, an average 10% increase in malnutrition is assumed until 2100. Malnutrition leads to decreased life expectancy (YOLL) and disability. Today 3.1 million children under 5 is estimated to die from starvation according to World Food Program (2016) and 684000 cases per year is registered among adults (Salomon et al, 2012). Assuming a 27 year reduction in life expectancy for adults, based on conditions in the poorest countries we obtain a total life expectancy decrease of 3.1*75+0.684*27 =251 million YOLL/year from malnutrition. 10% of that was assumed to be caused by climate change, i.e. 25.1 million YOLL/year. Divided by the accumulated CO_2 emission from 2012 until 2100 of the scenario RCP 6 (3885 Gton) and considering the contribution of CO_2 to climate change (88%), we get an average impact of 25.1E+6*88/3885*0.88=5E-7 YOLL/kg CO_2. Multiplication with the monetary value for a YOLL gives a damage cost of 2.5 E-2 €/kg CO_2.

IPCC estimates that 25 million children under 5 will be under-nourished the year 2050 (IPCC AR5 WGII, chapter 11, table 11-2.) It is assumed that the rest of the family also is starving, i.e. the total extent of malnutrition is around 120 million person-years per year for the period from 2012 to 2100, which equals 120*88 million. The accumulated CO2 emissions in the same period in the RCP 6 scenario is 3885 Gton CO2-equivalents and the contributions to the global warming is 88% from CO2. The average damage cost is therefore 120*88E+6/3885E+12*0.88*9550 = 2.3 E-2 €/kg, where 9550 is the value for 1 year of malnutrition.

The model linking heat stress and cold moderation to YOLL is based on correlation between temperature and excess mortality in cardiovascular deceases. A dose-response curve of relative mortality rate as a function of monthly average temperature was established by Steen (1999b) on the basis of a report by Weihe (1986) and findings from the heat wave in France 2003, (Kosatsky and Biggeri 2013)

The estimation of YOLL from flooding is based on IPCC AR5 WGII Chapter 11.4.2.2 quoting Dasgupta et al. (2009)

Kolstad and Johansson (2011) projected an increase of 8-11% in the risk of diarrhea in the tropics and subtropics in 2039 due to climate change (IPCC AR5 WGII Ch11). 2010, 1.4 million persons died in diarrheal diseases Lozano et al, (2012). According to Vos et al. (2012) diarrheal diseases extended to 8 million personyears 2010. This gives an average of 2.79E-09 YOLLs /kg CO_2 and 1.59E-08 personyears/kg CO_2 of disease corresponding to damage costs of 1.40E-04 €/kg CO_2 and 8.37E-05 €/kg CO_2 respectively.

Present global crop production is 2.9 billion tons (FAO 2013). IPCC WGII AR5 Chapter 7 figure 7-7 foresees an average 5 % decline in present agricultural areas (1% per decade) for the period 2012 to 2100. The world production is assumed to follow population growth, which means that there is a net decline of crop production capacity due to climate change of 88*2900000000000*9/6,8*0,05 = 1.69E+13 kg. Divided by the total emission of CO_2 during the period, compensated for CO_2's contribution to global warming and multiplied with the value of crop production capacity we get a damage cost of 8.42E-4 €/kg.

Another impact pathway is the decrease of fertile land due to sea level rise, caused by global warming. Bosello et al. (2006) estimate a land loss to 1.25E+5 km2. This impact will last for several 100 years. If an average fertility of 5000kg/ha is assumed during 500 years the production capacity loss will be 12500000*5000*500 = 3.12E+13 kg which if allocated to the next 100 years of emissions will result in 7.08E-3 kg of crop/kg CO_2 and a damage cost of 1.56E-3 €/kg CO_2.

The decline in production capacity for fruit and vegetables and for meat in the present agricultural areas is assumed to be similar as for crop, i.e. 5% and corresponding damage cost is calculated in the same way. Today's production of fruit and vegetables is 0.99 billion tons and of meat 0.39 billion tons (FAO 2013).

Forests cover about 4 billion hectares of land. An average production capacity is estimated to 3000 kg of dry wood/hectare and the average impact from climate change and increase of plus or minus a few % globally. Kramer et al (2000) indicates a growth of about 5% for boreal forests, while temperate and tropical forests may even be negatively influenced. AR5 WGII, chapter 4 reports on very different results for different areas and time periods in all three forest types (Boreal, temperate and tropical). This is also the conclusion of Kirilenko and Sedjo (2007). We therefore assume an average of 0 change.

IPCC states in AR5 WGII Chapter 3, 4.4 on the basis of Schewe et al., (2013): "Each degree of global warming is projected to decrease renewable water resources by at least 20% for an additional 7% of the world population." For RCP 6.0 this means about 1^{o}C as an average from 2012- to 2100 and that 0.07*9 = 0.63 billion persons living with water scarcity is affected. The average water withdrawal today is around 400-700 m3/person and year in countries at risk like Mexico, India and China. The decrease availability of water is therefore estimated to around, 0.07*9E+9*500m3/person*0.2 =6.3E+12 kg/year. Half of this is assumed to have drinking water quality. This means a loss of 6.28E-2 kg of drinking water and 1.26E-1 kg of irrigation water per kg of CO_2.

IPCC AR5 WGII, Ch 5.4.3.1 states that "Nicholls et al. (2011) estimate that without protection 72 to 187 million people would be displaced due to land loss due to submergence and erosion by 2100 assuming global mean sea level increases of 0.5 to 2.0 m by 2100. Upgrading coastal defenses and nourishing beaches would reduce these impacts roughly by three orders of magnitude. Hinkel et al. (2013) estimate the number of people flooded annually in 2100 to reach 170 to 260 million per year in 2100 without upgrading protection and two orders of magnitude smaller with dike (levee) upgrades, if global mean sea level rises 0.6 to 1.3 m by 2100." Here, the best estimate is set to 1 billion persons migrating during the 21st century resulting in an average of 2.27E-7 migrations/kg CO_2.

The impact on biodiversity is hardly possible to estimate quantitatively in a precise way, but some information is available in IPCC AR5 WGII, e.g. that 70% of the present population of birds will be affected of changing habitat. In order not to leave this important impact type out from the monetary valuation, and assumption of doubling the present threat to biodiversity is assumed. This means an impact of 2.27E-16 NEX/kg CO_2.

3.2.2 Emissions of Dinitrogen Oxide to Air

Dinitrogen oxide has a GWP 100 of 264.8 (IPCC 2013) which means that its damage cost are about 264.8 times as high as that of CO_2, i.e. 35.9 €/kg N_2O. There is a slight difference in that it has no CO_2-fertilizing effect, but instead a N-fertilizing effect. However both are small. The wood fertilizing effect of CO_2 results in few percent increase in wood production capacity as indicated by Kramer et al (2000). A two percent increase results in a benefit cost of 0.0002 € which is small compared to the total damage cost of CO_2, 0.135 €/kg. As seen below from the valuation of NOx emissions the benefit of the N- fertilizing effect, if all N_2O was oxidized to NOx, would be, 0.23 €, which may change the last third figure in the damage cost value 35.9 €/kg N_2O. This is not done here but may be done in a later version, when more is known about how much of the N_2O that is transferred to NO or NO_2.

3.2.3 Emissions of Methane to Air

GWP 100 for methane is 28.5 (IPCC AR5 WG1 Ch8). This gives a damage cost of 28.5*0.135 = 3.83 €/kg CH_4.

3.2.4 Emissions of Nitrogen Oxides to Air

The damage cost due to impacts from NO_x depends on several environmental mechanisms, such as acidification, oxidant formation, eutrophication, particle formation and climate change. In table 6, the results of 23 pathways models are shown.

A critical issue in estimating the total damage cost of NO_x is whether nitrates in secondary particles contribute to the health effects of PM2.5 or not. According to Rice et al. (2007), there is no evidence for chronic health effects, and as nitrates and sulfates are soluble in water, it seems reasonable to assume that chronic health effects from NO_x and SO_2 are negligible and only acute health effects occur. This means that the characterization factor and the damage cost for NO_X with respect to YOLL and the chronic lung effects from secondary particles is 0.

Impacts caused by pathways of climate change is modelled by multiplying the corresponding characterization factors for CO_2 with GWP 100 for NO_x, measured as NO_2, which is -48.4 if secondary effects from ozone and nitrate particles, including cloud effects, are included in the model (IPCC AR5 WG1 Ch8 table 8.A.3).

Risk assessments for NOx's impact on YOLL via oxidants are available from USA. Fann et al. (2011) are estimating YOLL from ozone to 36000/year at a mean ozone concentration of 48 ppb. Scaling up these estimates to a global level with an estimated similar average concentration, 36000/314*7200 YOLLs per year is obtained totally from ozone. The contribution from NOx to ground level ozone formation may be estimated by multiplying the emissions (AR5, WGI, Table 8.SM.19) of all ozone forming substances, mainly NOx (1.22E5 Gg/yr), CO (8.93E5 Gg/yr), NMVOC (1.6E5 Gg/yr) and methane (3.64E5 Gg/yr) with their respective POCP (Photo Oxidant Creation Potential), i.e. 0.62, 0.021, 0.029 (Labouze et al. 2004) and 0.008 respectively (Altenstedt & Pleijel, 1998). The contribution to ground level ozone from NOx is then 52.7% and the YOLLS caused by NOx are 36000/314*7200*0,527 = 4.35E+5. Global emissions of NOx as N is 3.72E+04 Gg (IPCC AR5 WG1 Table 8.SM.19). The average impact per kg of NO_x as NO_2 is thus 4.35E+5/37200000000*46/14 = 3.56E-6 YOLL/kg NO_x. The corresponding damage cost becomes 0.18 €/kg NOx.

NO_x reacts in the atmosphere to create nitrate particles. The impact of nitrate particles on lung diseases like asthma and severe COPD is assumed to be the same as PM2.5. Nitrates are estimated to contribute with 11% to the PM2.5 mass. The 11% originates from Squizzato et al. (2014) and represents an industrial urban area, and is believed to be more representative for average population weighted exposure than the 5-6% suggested by IPCC for the assessment of climate impact. The global emissions of NOx as N is 3.72E+04 Gg (IPCC AR5, Table 8.SM.19). This means that the average impact of NOx on asthma and severe COPD is 3.34E-6 and 2.61E-7 personyears/kg NOx respectively corresponding to damage costs of 7.19E-03 and 5.00E-03 €/kg NOx.

Van Dingenen et al. (2009) estimate the global loss of agricultural crop the year 2000 due to ozone to between 45 and 82 million metric tons of wheat, and 17–23 million metric tons for rice, maize and soybean. Avnery et.al (2011) estimated the global crop loss to between 79 and 121 million metric tons. A best estimate of 90 million tons is used. Divided by the global emissions of NO_x, as given in the paragraph above, we obtain a characterization factor of 7.36E-1 kg crop/kg NO_x as NO_2, and a damage cost of 0.16 €/kg NOx as NO_2.

NOx is a fertilizer, and has both negative and positive effects in freshwater and seawater. Too much N-nutrients cause oxygen deficiency and decrease fish growth, while moderate amounts stimulate fish growth.

According to Diaz & Rosenberg (2008), dead zones cover 245 000 km2. A typical production rate of 10 kg/ha, year will give a total loss of 2.45E+8 kg/year. FAO has recommended that the global catch should level out at 100 million tons in order for fishing to be sustainable. This corresponds to about 3 kg per ha if all ocean and sea areas are counted. Assuming 10 kg/ha for production and fishing at continental shelfs may thus be of a reasonable order of magnitude. Global emissions of NOx as N is estimated to 3.72E+04 Gg in IPCC AR5 (Table 8.SM.19). According to Galloway et al. (2004) the anthropogenic deposition of NOx to marine areas is 21 Tg N/year and 18 Tg for NH3 for the year 1990. About half of the global emission of NOx is deposited in oceans. The export from rivers to coastal areas is estimated to 47.8 Tg N/year. (F. Dentener et al., 2006). The emissions of BOD is estimated to 0.83 Tg Neq/yr. This means that about 21/(21+18+47.8 +0.83) = 0.24 of the contribution to oxygen deficiency, causing dead zones, come from NOx emitted to the atmosphere. The characterization factor is thus (2.45E+8)/(37200000000*46/14)*0,24 = 4.81E-4 kg fish&meat/kg NOx as NO_2 and the damage cost is 1.01E-3 €/kg NO_x as NO_2.

FAO has recommended that the global catch should level out at 100 million tons in order for fishing to be sustainable. The global deposition of NOx to oceans is about 40 Tg N/year. In the upper 100 meters, this will contribute to a 0.123% increase of reactive nitrogen. (The ocean area is 360 million km2, the average concentration of reactive nitrogen is 0.9 g/m3 and the added concentration from atmospheric deposition is 0,00111 g/m3 in the upper 100 m assuming a 1 year residence time) It is here assumed that the increase in fish catch is proportional to nitrogen availability, as nitrogen is rate limiting. This is a rough simplification as many other factors determine which catch is available. The increased fish catch therefore is proportional to the increased nitrogen ratio, i.e. 100000000000*(0.00111/0.9) = 1.23E+8 kg. Another way of estimating the increased fish productivity is to assume that all N contribute to fish growth. Fish contains about 2% N, why 40 Tg would result in 8E+8 kg fish at most. The figure 1.23E+8, therefore seems reasonable, and is used together with the same total emission as for dead zones, to calculate the characterization factor -2.42E-04 kg fish/kg NO_x as NO_2.

The estimation of the decrease of fish production from acidification is be based on an estimation of land areas where the critical load are exceeded (10%) and on the total fresh water catch of fish (10 million tons annually, globally as estimated by FAO). Only a part of the lakes in a region with excess sulphur deposition is acidified, normally those that are small and in the most upstream regions. A rough guess is that 20% of the lake area in regions where the critical load is exceeded is acidified to an extent that no fish is reproduced. This will correspond to a loss of 200 000 ton of fish annually. As SOx also is a cause of freshwater acidification, the contribution from NOx should not be 100%. As the global emission of SOx is 1.25E5 Gg (IPCC AR5, WGII, Table SM 8.19), which results in 1.25E5/64*2 = 3910 Gmoles of H+, compared to the = 2660 Gmoles H+ from NOx, an approximate estimate is that i kg NOx contributes with 2660/(2660+3910) = 40.5% to the acidification. The characterization factor therefore becomes -200000000*0.405/(37200000000*46/14) = -6.63E-4 kg fish/kg NOx as NO_2 and a damage cost of 1.39E-3 €/kg NOx as NO_2.

The decline in growth in Pine and Hardwood is around 1-2% at 0.015 ppm increased ozone concentrations when the total concentration is in the range 0.05-0.06 ppm, which is most common in rural areas. This is an interpretation of data given by Reich (1987). The global average ozone concentration is estimated to have increased by about 0.015 ppm since 1850 (Stevenson et al., 2013). The global wood production is estimated to approximately 1.5E+12 kg/year. The industrial wood consumption is 1.6E+9 m3 according to FAO. The decrease in wood production due to ozone is therefore estimated to 0.015*1.5E+12 kg per year. Global emissions of NOx as N is 3.72E+04 Gg (IPCC AR5 WGI Table 8.SM.19). NOx contributes to about 31 % of the anthropogenic ozone produced (Stevenson et al. 2013). The characterization factor is therefore 0.015*1.5E+12 /(3.72E10/14*46)*0.31 = 5.71E-2 kg wood/kg NOx as NO_2. The corresponding damage cost is 2.28E-3 €/kg NOx as NO_2.

Nitrogen is a rate limiting factor for wood growth in a large part of the world. About 40% of the land area in the temperate regions is covered with forests, and about 50% of the emissions of NOx are assumed to deposit on land areas. Most of the global emissions are estimated to origin in temperate regions. As half of the N is used by the trees in the wood structure (ratio experienced when fertilizing with calcium ammonium nitrate), as 11% of the forests have nitrogen deposition above the critical load (Dentener et al., 2006), and as the wood consists of 1% N, (on dry basis), 1 kg NOx will result in 0.4*0.5*0.5*(1-0.11)*14/46*100 =2.71 kg wood. The corresponding damage cost is -0.11 €/kg NOx as NO_2.

The share of species threatened by agricultural and forestry effluents in aquatic environments is 0.007 (IUCN, 2014). The characterization factor for NEX and the eutrophication pathway is 0.007/1.96E-12 = 1.37E-14 NEX/kg NOx, where 1.96E-12 is the same figure as used for eutrophication and dead zones. The damage cost becomes 7.70E-4 €/kg NOx as NO_2.

The added damage cost on the state indicators, for NOx, via the pathways listed in table 6, is 0.25 €/kg NOx as NO_2 if climate impacts are excluded and -6.15 €/kg NOx as NO_2 if the moderating effects on global warming is included. Whether it is reasonable to include uncertain climate impacts or not is a question of how the results are to be used.

Table 6. Damage cost estimated for NOx

State indicator	Unit	Pathway	Characteri-zation factor	Damage cost (€/ indicator unit)
YOLL	personyears	secondary particles	0.00E+00	0.00
YOLL	personyears	climate change	-3.14E-05	-1.57
YOLL	personyears	oxidant formation	3.56E-06	0.18
asthma cases		secondary particles	3.34E-06	0.01
COPD severe		secondary particles	2.61E-07	5.00E-03
malnutrition	personyears	climate change	-1.16E-04	-1.11
working capacity	personyears	climate change	-5.64E-05	-3.32

diarrhoea	kg	climate change	-7.72E-07	-4,05E-03
crop	kg	oxidant formation	7.36E-01	0.16
crop	kg	climate change	-1.85E-01	-0.04
fruit&veg	kg	climate change	-6.32E-02	-0.02
meat&fish	kg	climate change	-2.49E-02	-0.05
meat&fish	kg	eutrophication, dead zones	4.81E-04	1.01E-03
meat&fish	kg	N-nutrification of ocean	-2.42E-04	-5.09E-04
meat&fish	kg	acidification	2.18E-03	4.57E-03
wood	kg	oxidant formation	5.71E-02	2.28E-03
wood	kg	N-nutrification	-2.71E+00	-0.11
wood	kg	climate change	0.00E+00	0.00E+00
drinking water	kg	climate change	-3.04E+00	-0.01
irrigation water	kg	climate change	-6.08E+00	-0.01
migration	persons	climate change	-1.10E-05	-0.27
NEX	share, dimensionless	climate change	-2.15E-14	-6.14E-04
NEX	share, dimensionless	eutrofication	1.37E-14	7.70E-04
all		all, including climate effects of secondary particles		-6.15
all		all, including climate effects of secondary particles		0.25

4. Discussion

After having made all value choices, collected all numbers, and made all models, a number of questions arise:

1) Are the results of sufficient quality, and how we can validate the results?
2) What would it mean if other value-choices were made, such as system boundaries, equity weighting and assumptions about the future?
3) What future developments may be anticipated today?

4.1 Validation

It is difficult to compare with other monetary estimations of damage costs, as they differ in a number of ways. An example of such difficulties is shown in table 7. In table 7 a comparison is made between values obtained here and values recommended by the German Umweltbundesamt (UBA 2012). The values for CO_2 are of the same order of magnitude, but the values for NO_x differ significantly as UBA's values are based on local conditions and different impacts. This, in turn depends on a different goal and scope for the German assessment: to assist in German policy setting. In that context it would have been difficult to include moderating climate impacts from secondary particles, and perhaps pay people to emit more NO_x. As a user of the EPS method, it easier to exclude the values for climate change moderation from a default scenario than add new models and values.

Table 7. Comparison between values obtained for EPS2015d and values recommended by the German Umweltbundesamt

Emission	Damage cost estimation for Germany, €/kg (UBA 2012)	Damage cost according to this work €/kg
CO2	0.080 (0.040 -0.120)	0.135
NOx	15.4	-6.15 (0.25 without climate impacts)

Another way of validating the results is to compare the total global damage cost with the global productivity, and with the annual economic growth. If the damage costs are larger than global productivity, it would be surprising and very alarming, even if not impossible. If it would be lower than the economic growth it might indicate a sustainable development, at least from an economic point of view.

In table 8, the damage cost for some emissions and resources have been multiplied with the total global emissions and resource extractions and compared with the global "OECD-adjusted" value creation (productivity). The OECD-adjusted productivity is determined through multiplying average productivity per person in OECD (50 000€) with the global population. 50 000€ is the value used for YOLL, and represents the average lifetime productivity per year for an OECD inhabitant including household productivity. By using the YOLL value for productivity, we will have the same base for comparison of damage costs to human health and economic value creation. The data on SO_2, NMVOC, particles, emissions to water and land use is taken from Steen (2015a).The total damage cost calculated in this way is 14.5% of the global productivity (table 8). Table 8 indicates that more natural capital is consumed than the generation of global economic growth, which mostly has been between 2 and 3% during the last ten years. The damage cost of impacts from emissions is 3.5% which, despite a quite different assessment method, indicate the same order of sustainability deficit as the current ecological footprint measure: at present 1.5 earths (Global footprint network 2015).

Land use impacts contribute with about 1% of the total impact value, mainly because of land use in cities.

Table 8. Global damage cost from emissions and resource use

Emission/resource	Total damage cost. €	% of global productivity*
CO2	4.40E+12	1.22
CH4	1.27E+12	0.35
N2O	1.36E+12	0.38
NOx	-1.74E+12	-0.48
SO2	-8.65E+11	-0.24
NMVOC	2.21E+12	0.61
PM2.5	4.62E+12	1.28
BC (Black Carbon)	1.39E+12	0.39
land use in cities	3.33E+12	0.93
land use for mining	3.53E+11	0.10
other land use	1.96E+10	0.01
emissions of nutrients to water	1.90E+09	0.00
depletion of fossil resources	3.72E+12	1.03
depletion of ores and minerals	3.21E+13	8.91
	Sum	14.49

* calculated as the value of a YOLL times the global population

The major part of the damage cost is from depletion of ores and minerals. The element resources contributing most to this cost are shown in table 9.

Table 9. Damage cost from depletion of ores and minerals

Element in resource	Total damage cost. €	% of total productivity *
Au	5.25E+12	1.46
Rh	5.05E+12	1.40
Sb	2.96E+12	0.82
Fe	2.44E+12	0.68
Pb	2.08E+12	0.58
Te	1.82E+12	0.51
Cu	1.64E+12	0.45
Cd	1.55E+12	0.43

Pd	1.52E+12	0.42
Ag	1.46E+12	0.40
Ru	1.46E+12	0.40
Pt	1.15E+12	0.32
Ir	6.61E+11	0.18
Mo	5.68E+11	0.16
Zn	4.37E+11	0.12
other elements	2.04E+12	0.57

* calculated as the value of a YOLL times the global population

It seems reasonable that Au and Rh are at the top of the list in table 9. They are both very rare. Au is since long a central metal in human culture and Rh is one of the rarest metals on earth and subject to high demand as catalyst in cars. Sb is a medium scarce metal but is used frequently as an alloy substance. Fe is used in large amounts and is quite abundant.

Another way of examining the results is to calculate how much, impacts on each safeguard subject contribute to the total impact value. The results of such a sensitivity analysis are shown in table 10.

Table 10. Contribution to the total impact value from impacts on different safeguard subjects

Safeguard subject	% of total impact value
Ecosystem services	0.44
Biodiversity	0.07
Access to water	1.89
Abiotic resources	64.97
Human health	32.56
Economic subjects	0.06

The results shown in table 10 are somewhat surprising. One would expect a higher value for ecosystem services and biodiversity, as they are subject for many experts concern. Large projects like "The Millennium Ecosystem Assessment" (2005) and "The Economics of Ecosystems and Biodiversity" (2015) are indications of this. The significance of impacts on human health is probably uncontroversial.

If one would ask persons directly to rank impacts on ecosystems, human health and resources, you would get different results. Itsubu et al (2012) obtained a more even distribution between the safeguard subjects human health (26%), social assets (~resources) (14%), primary production (24%) and biodiversity (37%). These figures represent public perceptions in Japan when questions on values were asked at this level.

The difference between the results from our study and the one of Itsubo et al. may be explained by the fact that making evaluations on an aggregated level introduces much uncertainty among the respondents. It seems likely that in a choice between two alternatives with much uncertainty people tend to approach 50/50-levels. With the four alternatives given in the study by Itsubo et al, the results should tend to be near 25%. There is no reason to question their results as such; they most likely show peoples preferences at that level. A similar tendency is found in the Recipe 2008 method, where the weighting factors for ecosystems, human health and resources vary between 20 and 55% (Goedkoop et al. 2014).

In our work, we only use revealed preferences or calculated costs at a level representing everyday experiences, where the uncertainty is comparatively low for the people making valuations.

It is interesting to compare the values of biodiversity: 37% in the study of Itsubo versus the result of this study, 0.07%. A basic difference is that 37% represents stated preferences, i.e. willingness to pay to avoid damage to biodiversity, while 0.07% represents financial costs of meeting global biodiversity conservation targets.

4.2 Alternative Value Choices

Besides all value choices in impacts assessments, as identified in ISO 14044 (2006), there are several value choices in monetary assessments of environmental impacts. There are value choices with respect to 1) whose values that are assessed, 2) what methods to use to measure values and 3) assumptions made about the future.

In the EPS 2015d method the values are those of an average OECD inhabitant acting as a product developer or other decision maker. An alternative would have been to use a global average inhabitant. The values obtained would then have been lower and probably somewhat differently distributed among the safeguard subjects. But it had been more difficult to assess, as most information on preferences and costs originates from industrialized countries. The same would be the case if we tried to assess values from specific cultures.

Companies are often interested in their customers or stakeholders preferences. For example BASF has developed a special method for assessment of eco-efficiency (Saling, 2002), where experts are asked to rank the significance of different impact types.

The methods we used to measure monetary values market oriented. They measure revealed preferences, or estimate future preferences to be revealed from supply-demand curves. For e.g. labor and food there are existing markets, for abiotic resources market scenarios must be constructed. It could also be of interest to examine future scenarios for existing markets e.g. with shortage of food. Like for other basic needs, the WTP would increase to what it takes to produce it. The reproducibility of monetary values obtained with revealed preference is generally better than values obtained with stated preferences methods.

In the EPS 2015d method, there are several assumptions about the future that may be made in other ways. More optimistic scenarios of economic and technical growth may result in discounting future impacts and lead to lower values for long term impacts, such as climate change and depletion of abiotic resources. Discounting with 3% will decrease the net present value of an impact value 100 years from now with 95%. More pessimistic scenarios, like IPCC's worst reference scenario RCP 8.5 would give a CO_2 cost increase of 0.02 €/kg (15%), just for decreased working capacity.

One value choice of particular interest is how certain an impact model or cause-effect chain have to be to be included in the monetary valuation. In IPCC's latest report (Myhre et al. 2013) NOx, measured as NO_2 has a negative contribution to global warming, with a GWP 100 varying between – 3.3 to – 48.4 depending on which model that was chosen and how much of secondary atmospheric reactions that was included in the modelling. In the default version secondary reactions in terms of particle formation and decreased methane lifetime through ozone formation were included and a GWP 100 of -48.4 used, which gave a total negative monetary value for NOx of – 6.15 €/kg. If another model was used without secondary aerosol reactions and a GWP 100 of -3.3 (Fuglestvedt 2010) was used, the overall monetary value would be positive 0.25 €/kg. This is a dramatic change, which demonstrates that neglecting an uncertain but likely mechanism, because of uncertainty, would be controversial. In case NOx emissions contribute to a significant part of the damage cost for alternative product- or process concepts, a sensitivity analysis using both values is preferable.

4.3 Future Developments

There are two types of improvements that seem to be possible and beneficial. One is increased accuracy in modelling impact of greenhouse gases and abiotic resources; one is including more impacts, in particular positive externalities. In some cases, local impacts may also be assessed and valued, like water resources and urban climate. Improved models of greenhouse gas impacts depend to a large extent on the work in IPCC and their next assessment report. A similar situation exists for ecosystem services, where there are significant international programs. In case of abiotic resources, differentiation between different resource qualities may be possible. Using dilute and abundant resources should result in lower impact values than using high concentrated less abundant resources. Some positive externalities have been identified, such as capacity and efficiency of technology to satisfy basic needs, but so far no monetary measures have been assessed.

5. Conclusions

New knowledge of climate impacts, better global data on eutrophication, composition of earth's crust and red-listed species, has resulted in changed estimates for CO_2, CH_4, N_2O, NO_x and abiotic resources compared to the EPS estimate from 2000.

Two methodological choices are particularly important for the values obtained. One is the long term perspective and intergenerational equity. The other is the approach to uncertainty.

The added damage cost from global emissions and global use of natural resources exceeds the growth in global

GNP with this EPS type of calculation. Impacts on abiotic resources account for the largest damage cost with impacts on human health as the second largest.

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