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Using the budget constraint to monetarise impact assessment results

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ABSTRACT

Recent developments in Life Cycle Impact Assessment (LCIA) provide a basis for reducing the uncertainty in monetarisation of environmental impacts. The LCIA method "Ecoindicator99" provides impact pathways ending in a physical score for each of the three safeguard subjects humans, ecosystems, and resources. We redefine these damage categories so that they can be measured in terms of Quality Adjusted Life Years (QALYs) for impacts on human well-being, Biodiversity Adjusted Hectare Years (BAHYs) for impacts on ecosystems, and monetary units for impacts on resource productivity.

The monetary value of a QALY can be derived from the budget constraint, i.e. the fact that the average annual income is the maximum that an average person can pay for an additional life year. Since a QALY by definition is a life-year lived at full well-being, the budget constraint can be determined as the potential annual economic production per capita at full well-being. We determine this to be 74,000 EUR with an uncertainty estimate of 62,000 to 84,000 EUR. This corresponds well to the 74,627 EUR willingness-to-pay estimate of the ExternE project. Differences to other estimates can be explained by inherent biases in the valuation approaches used to derive these estimates.

The value of ecosystems can be expressed in monetary terms or in terms of QALYs, as the share of our well-being that we are willing to sacrifice to protect the ecosystems. While this trade-off should preferably be done by choice modelling, only one such study was found at the level of abstraction that allows us to relate BAHYs to QALYs or monetary units. Stressing the necessity for such studies, we resort to suggest a temporary proxy value of 1400 EUR/BAHY (or 52 BAHY/QALY), with an uncertainty range of 350 to 3500 EUR/BAHY.

The practical consequences of the above-described monetarisation values has been investigated by combining them with the midpoint impact categories of two recent LCIA methods, thus providing a new LCIA method with the option of expressing results in both midpoints and an optional choice between QALY and monetary units as endpoint. From our application of the new method to different case studies, it is noteworthy that resource impacts obtain less emphasis than in previous LCIA methods, while impacts on ecosystems obtain more importance. This shows the significance of being able to express impacts on resources and ecosystems in the same units as impacts on human well-being.

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1. Introduction

The applicability of cost-benefit assessments (CBA) is affected by the high uncertainty in relation to monetarisation of environmental impacts (see e.g. Turner et al., 2004). CBA has also been criticised for incompleteness (see e.g. Bos and Vleugel, 2005). Recent developments in Life Cycle Impact Assessment (LCIA) offer a basis for reducing both the uncertainty in monetarisation and the completeness problem.

The UNEP/SETAC framework for LCIA (Jolliet et al., 2004) operates with three overall safeguard subjects (humans, ecosystems, resources), fundamentally parallel to the "People, Planet, Profit" distinction for sustainability made popular by WBCSD (World Business Council for Sustainable Development). Since the three safeguard subjects are logically exhaustive (any item must be either human or non-human, biotic or abiotic, intrinsic or instrumental), they provide a complete framework for all imaginable values for protection.

The LCIA method "Ecoindicator99" (Goedkoop and Spriensma, 2001) was the first to provide impact pathways that ended at a physical score for each of the three safeguard subjects humans, ecosystems, and resources. In the following, we shall elaborate a novel procedure for monetarising these physical scores. The procedure is aimed at reducing some of the previously encountered uncertainty and incompleteness in monetarising environmental impacts.

2. Defining the damage categories

For each of the three safeguard subjects (humans, ecosystems, resources) we specify a common measurement unit. Our measurement units are slightly adjusted compared to the units for impact or damage applied in the "Ecoindicator99" (Goedkoop and Spriensma, 2001).

Within the safeguard subject "humans" we define the damage category as "Human well-being" with the measurement unit Quality Adjusted Life Year (QALY). This measurement unit is identical to the Disability Adjusted Life Year (DALY) used by Goedkoop and Spriensma (2001), except for a reversal of signs (QALY measures a positive state, while DALY measures damage, i.e. 1 QALY = −1 DALY) and that while the disability adjustment is limited to health issues, the quality adjustment may also apply to social aspects, such as infringements on autonomy and equal opportunities (Weidema, 2006). The reversal of sign is of little consequence and is mainly made to ensure consistency with the traditional definitions and usage of EUR and QALYs in previous work in the field of CBA and health economics. The most critical value choice in the DALY and QALY concepts is that all individuals are given equal weight irrespective of socio-economic status.

Within the safeguard subject "ecosystems", we define the damage category as "Biodiversity" with the measurement unit Biodiversity Adjusted Hectare Year (BAHY). This measurement unit is identical to the PDF m^2 years used by Goedkoop and Spriensma (2001), where PDF is an abbreviation of Potentially Disappeared Fraction of species, except for the more convenient size of the unit (1 ha = 10,000 m^2), a reversal of signs (BAHY measures a positive state, while PDF m^2 years measure damage, i.e. 1 BAHY = −10,000 PDF m^2 years), and that we specify the damage relative to the number of endemic species under natural conditions. It would be possible to define the damage category wider, e.g. in terms of Quality Adjusted Hectare Years, to capture also other aspects of ecosystems quality than just biodiversity. However, in practice, the currently available operational measures of ecosystems quality are all related to biodiversity, so a more encompassing name would be presumptuous. The most critical value choice in the PDF m^2 years and BAHY concepts is that all species are given equal weight.

In giving equal weight to all individuals or species, the QALY and BAHY concepts have a level of abstraction that may complicate their application for valuation in e.g. choice modelling, but at the same time gives them the level of neutrality required to reduce arbitrariness and uncertainty from specific contexts.

For the safeguard subject "resources" we define the damage category as "resource productivity" measured as the future economic output in monetary units. In practice, we use "EUR_{2003}", i.e. the currency unit Euro at its average value in year 2003. The conversion factor to USD is close to 1 for this year. To measure the impact of mineral resource use on future generations, Goedkoop and Spriensma (2001) used "MJ" additional energy required for future extraction as a result of current dissipation. However, dissipation of mineral resources is only a small part of the non-internalised impacts on resources caused by current human activities. Examples of much more important impacts are the lost production due to health impacts on the labour resource, and the lost agricultural output resulting from photochemical ozone impacts; see Table 3, the notes to Table 4, and Weidema et al. (submitted for publication). Since all losses of resource productivity, including the additional efforts needed for future extraction of mineral resources, can be measured directly as the economic production value foregone, it appears reasonable to use a monetary rather than a physical unit as the common unit of measurement.

3. Using the budget constraint to obtain the monetary value of a QALY

In this section, the monetary value of a QALY is derived from the overall budget constraint, and the resulting value compared to and discussed in the context of the results of other methods to derive the monetary value of a QALY.

The budget constraint, i.e. the fact that the average annual income is the maximum that an average person can pay for an additional life year, provides an upper limit for the monetary value of a QALY. Since a QALY by definition is a life-year lived at full well-being, the budget constraint can be determined as the potential average annual income at full well-being, which is equal to the potential annual economic production per capita.

Since a QALY conceptually covers all aspects of human well-being that one would be willing to pay for, all income will on average be spent on total production to maintain full well-being, providing that there is no long-term change in capital stock. Therefore, the potential average annual income at full well-being also provides a lower limit for the monetary value of a QALY. We may thus conclude that there is a conceptual equivalence between the monetary value of a QALY and the potential economic production per capita.[1]

The potential annual economic production per capita is calculated by Weidema (2005), arriving at a value equivalent to 74,000 EUR_{2003}. An uncertainty range of 62,000–84,000 EUR_{2003} per QALY can be estimated. The potential annual economic production is calculated by taking the current Gross Economic Product (GEP)[2] of USA (39,500 EUR_{2003}) as a starting point – noting that USA has the highest GEP in the World, when ignoring a few untypical economies based heavily on oil or banking – and multiplying it by the factor 1.87 derived in Table 1 to take into account current impacts from unemployment and underemployment, health impacts, trade barriers and missing education. Except for these impacts, the current difference between the USA and the global average is assumed to be due to lacking physical and social infrastructure. There are no other apparent reasons that the GEP of countries should differ.

It is interesting to note that the willingness-to-pay studies performed as part of the recent update of the ExternE methodology (Markandya et al., 2004) result in a recommended undiscounted value of a life year of 74,627 EUR, i.e. practically the same as our value of 74,000 EUR_{2003} for the budget constraint calculated as the potential annual economic production. While this is purely a coincidence, it confirms that our value is in a reasonable range. The ExternE update is characterised by specifically seeking to address small risk increases from involuntary exposure and is therefore regarded as more relevant for policy analysis of pollution impacts than previous studies.

Other estimates in the value-of-life literature – 42 in total – were reviewed by Hirth et al. (2000), who found a strong dependency on the method applied. They found median values of 25.000 USD_{1997} (approximately 23,000 EUR_{2003}) per QALY for studies using the human capital approach, and 160,000 USD_{1997} (approximately 150,000 EUR_{2003}) per QALY for contingent valuation studies, when using a 3% discounting rate (corresponding to 90,000 EUR_{2003}/QALY without discounting). For studies using revealed preferences, the median values were 93.000 USD_{1997} for non-occupational safety and 428.000 for job-risk studies, both calculated for a 3% discount rate. The human capital approach only includes the value of the earning ability under current economic conditions. It is therefore expected that the values derived by this method are lower than our value derived from the potential economic production, which takes into account the full earning ability when current barriers for full economic production are removed. The higher values of the willingness-to-pay studies can be explained by the difficulties to adequately account for the budget constraint in this type of studies. Also, studies based on contingent valuation and revealed preferences most often assess voluntary risk or risk aversion behaviour, and the derived values can best be interpreted as the individuals' evaluation of impacts that occur to themselves, rather than a value that is applicable for general policy purposes, see also the discussion in Markandya et al. (2004). It is obvious that some people in some situations will be willing and able to pay more than the global average budget constraint for an extra QALY, and that other people will be less able (and possibly also less willing). However, the global nature of the QALY concept, i.e. that a QALY has the same value for all individuals, supports that the value of a QALY should be derived from the global average budget constraint, rather than the budget constraints and valuations of specific individuals.

The willingness-to-pay estimate of the ExternE project of 74,627 EUR is provided with an uncertainty estimate of 27,000–225,000 EUR (Markandya et al., 2004). An important cause of the uncertainty found in willingness-to-pay studies is that the results vary with the geographical location, population and context. While this may indeed provide relevant values for a specific context, it is less useful for deriving values for an abstract concept like QALYs, which is intended to be

Table 1 – Ideal economic production relative to the current economic production of the USA

	Ideal economic production relative to the current economic production of the USA	Estimated range	Basis of calculation
Unemployment and underemployment	1.02	1.01–1.03	[1]
Health and other work-disabling impacts	1.19	1.16–1.22	[2]
Effect of trade barriers	1.05	1.01–1.08	[3]
Education	1.46	1.33–1.56	[4]
Product of all the above	1.87	1.57–2.12	

[1] The ideal workforce of 0.485 per capita (97% of a labour force participation of 0.5 at 3% unavoidable frictional and structural unemployment) expressed relative to the current workforce of 0.46 per capita (94.2% of a labour force participation of 0.488 at 5.8% unemployment). Only 30% of the difference between the ideal and the current situation has been included, due to the offsetting impact on household production.
[2] A situation of full health expressed relative to the current health gap of approximately 16% (Mathers et al., 2004).
[3] Ideal without trade barriers expressed relative to the current situation, which involves a loss of 5 times the 1% of developed world GDP lost due to trade barriers on goods according to Newfarmer (2001).
[4] Ideal average 18 years of schooling, involving a 6.8% increase in GDP per year of additional schooling between 12 years and 18 years, relative to the current US adults' average 12.2 years (Barro and Lee, 2000), i.e. 1.068E(18–12.2).

[1] One reviewer suggested that part of the potential might be realised in the form of increased leisure, in which case the potential economic production would be reduced. However, from a valuation perspective, the value (shadow price) of such a potential change in leisure preference should also be included in the value of a QALY, which means that this would remain unaffected.

[2] GEP is defined by Ironmonger (2004) as the sum of the Gross Domestic Product (GDP) and the Gross Household Production (GHP). The current GHP can be estimated at about 0.5 of the current GDP.

globally applicable for aggregation of impacts in many different contexts. When applying the overall budget constraint, the uncertainty on the monetary value of a QALY is reduced to a range of 62,000–84,000 EUR_{2003} per QALY, derived by applying low and high estimates for each of the constituting components in Table 1, where the range for the overall factor is calculated to 1.57–2.12.

4. Expressing ecosystem impacts in terms of human well-being

Lack of willingness-to-pay values for general impacts on ecosystems has been a major obstacle for the inclusion of such impacts in CBAs. For example, in his otherwise thorough study of the economic impacts of climate change, Tol (2002) resorts to applying a fixed value based on "warm glow", i.e. a value that does not change with increasing impacts on ecosystems.

As a more solid alternative to willingness-to-pay estimates, choice modelling is gaining ground as a way to value ecosystem impacts (see the survey of Hanley et al., 2001, for examples for specific ecosystems and geographically limited ecosystem services, and Itsubo et al., 2004 for an example using species-extinction). Choice modelling is already widely used for the health state evaluations that allow us to aggregate different impacts in human well-being into the common unit of QALYs, see e.g. Hofstetter (1998), Goedkoop and Spriensma (2001), Jolliet et al. (2003). For a decision maker that accepts the use of choice modelling to obtain health state evaluations for environmental midpoint indicators, it should also be acceptable to apply choice modelling as a procedure to obtain an expression of the severity of ecosystem impacts in terms of QALYs or monetary units. For example, it could be investigated what sacrifice in terms of disabilities or lost life years would be acceptable to protect a certain ecosystem area, or put in other terms: what reduction in life quality is regarded as equivalent to the loss of a certain ecosystem area.

However, although choice modelling has been applied to specific ecosystems and geographically limited ecosystem services, only one study (Itsubo et al., 2004) have yet been made at the level of abstraction that allows us to obtain a measure of BAHYs in terms of QALYs or monetary units. In anticipation of, and to stimulate the execution of, more such choice modelling studies, we resort to suggest a proxy value.

In an initial attempt (Koneczny and Pennington, 2007), we started our derivation of a proxy value by comparing the global terrestrial species-area of 13×10^9 ha years to the global human population 6.2×10^9 people, noting that if these were given an equal weighting in a valuation, this would result in an "exchange rate" of 2.1 ha years per human life-year. We could also express this as 2.1 BAHY/QALY, since QALYs represent human life years at full well-being, corresponding to BAHYs representing hectare years of nature in its unaffected state. To adjust for the fact that ecosystem biodiversity and humans are not in practice given equal weight, we suggested that the protection target of 10% of the global ecosystems called for in the Convention on Biological Diversity could be compared to an ultimate protection target for human well-being of 100%, giving us an adjustment factor of 10 for the "exchange rate" between biodiversity and human well-being. The resulting value of 21 BAHY/QALY or 0.048 QALY/BAHY could be understood to mean that the full protection of an ecosystem of 21 ha (210,000 m^2) for one year has the same value as an extra life-year at full health for one person.

To express BAHYs in monetary units, we used the above-derived value of a QALY, thus arriving at a value of 3500 EUR/BAHY (74,000 EUR/QALY divided by 21 BAHY/QALY). Noting that the current human activities engage approximately 50% of natural ecosystems (37% of NPP according to Imhoff et al., 2004; 13% as a central estimate of the global species-area lost due to climate change, following Thomas et al., 2004), the adjustment factor of 10 implies that this the overall damage would be equivalent to a 5% loss of all potential QALYs or 0.05 QALY/person-year. In monetary terms, this may be interpreted as 5% of the potential income or 3700 EUR/person-year.

However, we note that the value of 3500 EUR/BAHY is one order of magnitude larger than the range of 63–350 EUR per ha of ecosystem protected suggested by the ExternE study (Bickel and Friedrich, 2005) for acidification and eutrophication. This value was derived from what they call a "second-best" method of revealed preferences from political negotiations.

The choice modelling study of Itsubo et al. (2004) used the normalised environmental impacts of an average Japanese (0.54 million DALYs versus the extinction of 1 species annually) and obtained monetarised values of 9.7 million JPY/DALY (approximately 68,000 EUR/DALY) and 4.8E+12 JPY (34 E+9 EUR) per species-extinction, or a weighting factor of 1.2 on the normalised values. Itsubo et al. (2003) present values for different land uses (e.g. road construction) with an average impact of 4E-8 species-extinctions per ha. With a corresponding value of 0.88 BAHY/ha for similar land uses, we obtain 4.5 E-8 species-extinctions/BAHY or 1500 EUR/BAHY.

Finally, we note that the current environmental protection expenditures in developed countries are at 1–2% of GDP. Although this is not the same as the marginal willingness-to-pay for additional ecosystem protection above the current level, it may – together with the above observations – indicate that our initial suggested value of 5% of the potential income for ecosystem protection is likely to be an upper bound. Using the ExternE values as a lower bound, we have an order of magnitude range for the "correct" value of a BAHY, i.e. it is likely to be anywhere between 350 and 3500 EUR/BAHY. In the following exemplary applications, we used a value corresponding to valuing the current global ecosystem impacts at 2% of the potential income, i.e. 1500 EUR/person year or 1400 EUR/BAHY, stressing that this is purely a proxy value in order to show the importance of being able to express ecosystem damage in monetary terms, waiting to be replaced by better estimates to be made directly by choice modelling.

5. On the additivity of the three damage categories

That the impacts on the three damage categories are additive is demonstrated by the following reasoning: In a world without externalities, the GDP would be 74,000 EUR/capita, as shown in the previous section. This would also be the money we could spend. The potential value of production and consumption is thus 2×74,000 EUR=148,000 EUR/capita. We loose some of our production value of 74,000 EUR because of impacts on production, i.e. our present education-corrected global GDP is not 74,000 EUR/capita but only 10,300 EUR (the relationship 10,300/74,000 EUR=14%, which could be called our current production efficiency). Furthermore, we loose some of our potential 74000 EUR worth of life quality because of impacts on human health and ecosystems. Let us assume that these impacts can be calculated on a global scale to be approximately 51,000 EUR (not all of them attributable to products or even to human activities). The ratio (74,000−51,000)/74,000=31% could be called our consumption efficiency. The overall production and consumption efficiency is therefore currently (14+31)/200=23%, which indeed shows an ample room for improvements.

6. Choosing QALYs or monetary units to express overall impact?

The relationship between QALYs and potential human economic production is an equivalence, i.e. while the potential annual per capita economic production of 74,000 EUR_{2003} puts a limit on our ability and willingness to pay for a QALY, an additional life year at full well-being (i.e. an additional 1 QALY) provides us an additional potential economic production of 74,000 EUR_{2003}. In comparison to other monetarisation methods, our procedure of using the budget constraint has the advantage that the resulting values can be interpreted as a proportion of the potential human economic production, and thus directly comparable to the impacts on resource

Table 2 – Summary of damage (endpoint) characterisation factors for the midpoint impact categories in Stepwise2006 v.1.2, and aggregation of all impacts into a single-score indicator measured in EUR

Impact category	Unit of characterised values at midpoint	Impact on ecosystems		Impacts on human well-being		Impacts on resource productivity	All impacts aggregated
		BAHY/ characterised unit at midpoint [1]	EUR/ characterised unit at midpoint [2]	QALY/ characterised unit at midpoint [3]	EUR/ characterised unit at midpoint [4]	EUR/ characterised unit at midpoint [5]	EUR/ characterised unit at midpoint [6]
Acidification	m^2 UES	5.5E-06	7.7E-03				7.7E-03
Ecotoxicity, aquatic	kg-eq. TEG wat.	5.0E-09	7.1E-06				7.1E-06
Ecotoxicity, terrestrial	kg-eq. TEG soil	7.9E-07	1.1E-03				1.1E-03
Eutrophication, aquatic	kg NO_3-eq.	7.2E-5	0.10				0.10
Eutrophication, terrestrial	m^2 UES	8.9E-06	1.3E-02				1.3E-2
Global warming	kg CO_2-eq.	5.8E-05	8.2E-2	2.1E-08	1.6E-03	−3.7E-04	8.3E-2
Human toxicity	kg C_2H_3Cl-eq.			2.8E-06	0.21	6.4E-02	0.27
Injuries, road/work	fatal injuries-eq.			43	3.2E+06	9.9E+05	4.2E+06
Ionizing radiation	Bq C-14-eq.			2.1E-10	1.6E-05	4.8E-06	2.0E-05
Mineral extraction	MJ extra					4.0E-03	4.0E-03
Nature occupation	m^2 arable land	8.8E-05	0.12				0.12
Ozone layer depletion	kg CFC-11-eq.			1.1E-03	78	24	100
Ph.chem. ozone – veg	m^{2}*ppm*h	6.59E-08	9.3E-05			2.8E-04	3.7E-04
Respiratory inorganics	kg PM2.5-eq.			7.0E-04	52	16	68
Respiratory organics	Pers*ppm*h			2.6E-06	0.20	6.1E-02	0.26

[1] Characterisation factors from Weidema et al. (submitted for publication), based on Goedkoop and Spriensma (2001), Potting and Hauschild (2005), Humbert et al. (2005), and Thomas et al. (2004).
[2] Values from column [1] multiplied by 1400 EUR/BAHY.
[3] Characterisation factors from Weidema et al. (submitted for publication), based on Tol (2002), Humbert et al. (2005), Mathers et al. (2004), Hofstetter (1998), and Hauschild and Potting (2005).
[4] Values from column [3] multiplied by 74,000 EUR/QALY.
[5] Characterisation factors from Weidema et al. (submitted for publication), based on Tol (2002), Miller et al. (2000), and Goedkoop and Spriensma (2001).
[6] Sum of values from column [2], [4] and [5].

productivity (production output lost due to health impacts, lost agricultural output resulting from pollution, etc.). We may therefore use this equivalence to translate the impacts on economic production into QALYs, rather than translating QALYs into monetary units. This has the advantage that QALYs express an (ultimate) intrinsic value, while monetary units merely represent instrumental values. This option may be of particular interest when the endpoint results are to be communicated to persons that do not favour monetarisation. Another advantage is that impacts expressed in QALYs are relatively stable over time, while monetary units are more volatile.

7. Findings from applying the endpoint modelling to case studies

The practical consequences of the above-described endpoint modelling has been investigated by integrating it with the midpoint impact categories of two recent LCIA methods (EDIP2003 and IMPACT2002+), extended to the damage categories of "Ecoindicator99", thus providing a new LCIA method (named Stepwise2006) with the option of expressing results in both midpoints and an optional choice between QALY and monetary units as endpoint. The full documentation of Stepwise2006 is available via www.lca-net.com/projects/stepwise_ia/ or in Weidema et al. (submitted for publication).

We have applied the Stepwise2006 method at different stages of development to a number of case studies (Koneczny and Pennington, 2007; Weidema and Wesnaes 2006, 2007; Weidema et al., in press). From these experiences, we find that the impact category for natural resource use is now assigned less importance than in previous LCIA methods, as a result of expressing impacts on resource productivity in comparable monetary units rather than in physical values. Conversely, impacts on ecosystems now obtain higher importance in the results than in previous LCIA methods. This shows the importance of being able to express impacts on the three safeguard subjects in the same units.

8. Estimating the relative importance of environmental impact categories

Table 2 provides a summary of the characterisation factors for each of the midpoint impact categories of the Stepwise2006 LCIA method. As mentioned, the relationship between QALY and EUR, as applied in Table 2, is an equivalence. Thus, all values in EUR in Table 2 may as well be expressed in QALY, by using the conversion ratio 1.35E-5 QALY/EUR.

The relative importance of the different environmental impacts is shown in Table 3, obtained by multiplying the monetarised values for each midpoint impact category in Table 2 by their respective normalisation references, which express the total midpoint impacts in Europe in year 1995.

This shows that four impact categories (global warming, injuries, nature occupation, and respiratory inorganics) make up 92% of the total monetarised impacts from the included impact categories. Important impact categories that are not yet included in the Stepwise2006 method are invasive alien species and traffic noise.

9. Comparison to traditional monetarisation methods

Earlier monetarisation studies have primarily obtained their values from stated preferences (via contingent valuation or

Table 3 – Normalisation references and total impacts in EUR per person in Europe for year 1995

Impact category	Unit of characterised values	Normalization reference (Europe 1995)	Source	Total impact per person
		Characterised unit/person-year		EUR/year
Acidification	m^2 UES	2200	[1]	17
Ecotoxicity, aquatic	kg-eq. TEG water	1,360,000	[2]	10
Ecotoxicity, terrestrial	kg-eq. TEG soil	2350	[2]	2.6
Eutrophication, aquatic	kg NO_3-eq.	77	[4]	7.9
Eutrophication, terrestrial	m^2 UES	2100	[1]	26
Global warming	kg CO_2-eq.	10,600	[3]	880
Human toxicity	kg C_2H_3Cl-eq.	219	[2]	59
Injuries, road or work	fatal injuries-eq.	0.000142	[4]	590
Ionizing radiation	Bq C-14-eq.	533,000	[2]	11
Mineral extraction	MJ extra	292	[2]	1.2
Nature occupation	m^2 arable land	3140	[2, 4]	390
Ozone layer depletion	kg CFC-11-eq.	0.204	[2]	21
Photochemical ozone - Vegetation	m^{2}*ppm*hours	140,000	[1]	52
Respiratory inorganics	kg PM2.5-eq.	8.8	[2]	590
Respiratory organics	Person*ppm*h	10	[1]	2.6
Sum of the above (rounded)				2650

[1] Hauschild and Potting (2005).
[2] Humbert et al. (2005).
[3] Gugele et al. (2005).
[4] Weidema et al. (submitted for publication).

choice modelling) or from revealed preferences. The method applied for the Stepwise method (i.e. obtaining the monetary values directly via the overall budget constraint in terms of the potential human economic production), requires that all impacts are first expressed relative to an overall concept of well-being (such as QALYs), which has only recently become possible, especially as a result of the pioneering work of Goedkoop and Spriensma (2001) in developing the Ecoindicator99 method.

In general, previous studies combine a number of different methods for monetarisation and solicit separate values for specific pollutants, disabilities and environmental compartments. For example, the ExternE study (Bickel and Friedrich, 2005) applies damage values for impacts on health, agriculture and buildings, but resort to preferences revealed in political negotiations for impacts on ecosystems, and a mixed approach for global warming impacts. Furthermore, morbidity and mortality are valued separately, combining different monetarisation studies for different diseases and health endpoints. The more separate studies are combined, the larger the risk of inconsistencies.

Table 4 – Comparison of the Stepwise monetary endpoint values to the summary values in Turner et al. (2004)

Substance	Previous studies as reviewed by Turner et al. (2004)	Stepwise2006	Comment
CO_2	1–55	83	[1]
CO	2	450	[2]
NO_x	2200–42,000	9700	[3]
PM2.5	2900–435,000	68,000	[4]
PM10	2600–330,000	36,000	[4]
SO_2	2500–23,000	5400	[5]
VOC	725–2200	250	[6]

All values in EUR_{2003} per Mg emission.
[1] 98% of our value is ecosystem impact, while the previous studies have generally not quantified the ecosystem impact. Thus, the value of previous studies mainly captures health and resource productivity impacts.
[2] The value of 450 EUR is composed of health impacts (70 EUR), agricultural impact (171 EUR), ecosystem impact (57 EUR), global warming impact (130 EUR), and human resource impacts (21 EUR). The 2 EUR value of previous studies is probably due to insufficient physical modelling rather than differences in monetarisation.
[3] The value of 9700 EUR is composed of health impacts (6600 EUR), human resource impacts (2100 EUR), ecosystem impacts (600 EUR), and agricultural impact via photochemical ozone (400 EUR). The values of previous studies are dominated by the health impact, but also include small contributions from fertilization effect (a benefit of 200 EUR) and effects on buildings (300 EUR), both of which we have ignored in Stepwise2006, due to their relatively low importance.
[4] The PM values are for health impacts, except for a small contribution of 200 EUR/Mg PM10 for impacts on buildings, which we have ignored in this study, due to the low importance.
[5] The value of 5400 EUR is composed of health impacts (4000 EUR), human resource impacts (1250 EUR), and ecosystem impact (150 EUR). The values from previous studies are also dominated by the health impact, with 370–962 EUR impacts on buildings, 14 EUR impact on agriculture, and 8 EUR impact on ecosystems.
[6] The value of 250 EUR is composed of health impacts (20 EUR) including human resource impacts, agricultural impact (170 EUR) and ecosystem impacts (60 EUR), while the previous studies have generally not quantified the ecosystem impact. Turner et al. (2004) also give recommended values for the UK based on a study by Watkiss et al. (2004), where the values for health impacts are 4–600 EUR and the value for agricultural impact is 380 EUR. These more recent values are thus closer to our estimates.

In our approach, we have sought to reduce the need for separate monetarisation exercises, by suggesting that all human health and ecosystem impacts be measured by one indicator (QALY) and by then assessing the monetary value of this overall indicator. This does not eliminate uncertainty and the need for assumptions, but it does increase the consistency and transparency of the assumptions made.

An overview of monetarisation studies has recently been provided by Turner et al. (2004). Table 4 shows the values of Stepwise2006 compared to the values in the summary table of Turner et al. (2004) translated to EUR, using the exchange rate of 1.45 EUR/GBP.

Important impacts are left un-monetarised in previous studies (see e.g. Bos and Vleugel, 2005). Most studies do not provide consistent damage values for ecosystem impacts. This is especially problematic for global warming, where the ecosystem impact is dominating, but also the important impact from land use is left un-quantified in most studies.

10. Outlook

Expressing all environmental impacts in QALYs and using the budget constraint to establish an equivalence between QALYs and monetary units, opens up for seamless integration of new impact categories, e.g. for social and economic impacts, which may also be expressed in either QALYs or monetary units (Weidema, 2006), thus allowing for continuous increases in completeness of LCIA-based CBAs.

As any endpoint method will include a number of assumptions that may be controversial, a wider scientific and stakeholder review procedure is needed to approach consensus on the procedures and values used. This is especially relevant for the application of the overall budget constraint to derive the value of a QALY, a procedure which has not been attempted earlier. Also, to replace our proxy value for the severity of ecosystem impacts, a proper choice modelling study should be performed, preferably in conjunction with a larger study to obtain consistent values for a larger number of issues, and including calibration to the values derived in the “Global burden of disease” study (Mathers et al., 2004).

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