Supplementary Materials: Towards a Conceptual Framework for Social-Ecological Systems Integrating Biodiversity and Ecosystem Services with Resource Efficiency Indicators

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1. List of Indicators Entering the RACER Evaluation

Table S1. List of Indicators Entering the RACER Evaluation.

RU	= resource use	
RE	= resource efficiency	
EI	= environmental impact	
	Selected Indicators	**Unit**
Energy		
RE	Energy productivity (GDP/TPES) (ter.)	EUR/toe or EUR/J
RE	Energy productivity (GDP/Total Net Energy Consumption) (res.)	EUR/toe or EUR/J
RU	Energy dependency (imp/TPES) (ter.)	%
RU	Energy dependency (imp/Total Net Energy Consumption) (res.)	%
RU	Renewables/TPES (ter.)	%
RU	Renewables/Total Net Energy Consumption)(res.)	%
RU	TPES total primary energy supply	toe or J
RU	Total Net Energy Consumption) (res.)	toe or J
RU	Final energy consumption (FEC) (ter.)	toe or J
RU	Total Energy Requirement (res.)	toe or J
RU	”Energy footprint” (res.)	toe or J
EI	Fuel use/natural stock	%
EI	Fuel use/quality of stock	
Material		
RE	Material productivity (GDP/DMC)	EUR/kg
RE	Material productivity (GDP/RMC)	EUR/kg
RE	Material productivity (GDP/TMC)	EUR/kg
RU	Import dependence (imp/DMC)	%
RU	DMC domestic material consumption	t
RU	DMI direct material inputs	t
RU	RMI raw material inputs	t
RU	RMC raw material consumption	t
RU	TMR total material requirements	t
RU	TMC total material consumption	t
RU	PTB physical trade balance	t
RU	RTB raw material trade balance	t
EI	EMC environmentally weighted material consumption	
EI	Macro LCA	
EI	Material use/natural stock	%
EI	Fish catch outside safe biological limits	%
Water		
RE	Water productivity (GDP/water appropriation)	EUR/m^3
RU	Water abstraction (green and blue water)	m^3

RU	Water consumption (green and blue water)	m^3
RU	Water footprint (green and blue water)	m^3
EI	WEI water exploitation index	%
EI	WEI +	%
EI	Urban waste water treatment	%
EI	Available freshwater resources	m^3/capita
EI	Chlorophyll in transitional, coastal and marine waters	μg/L
EI	Nutrients in freshwaters	g/L or μMol/L
Land Use		
RE	Land productivity	EUR/ha
RE	Forest annual fellings as a share of net annual increment	%
RU	Artificial land or built-up area	ha
RU	Land Footprint/Actual Land Demand	ha
EI	Ecological Footprint	ha
EI	Fragementation of ecosystems	
EI	(Gross) Nutrient balance (N and P)	kg N/hectare (/year)
EI	HANPP human appropriation of net-primary production	%
EI	Soil erosion	kg/ha/year
EI	LEAC	
EI	eHANPP embodied HANPP	misc.
EI	Carbon content in soils	%
EI	Species diversity (Distribution & abundance)	INDEXed trends
EI	Designated areas (ha protected)	hectares or % protected
EI	Common bird index	index
CO_2/GHG Emissions		
RE	CO_2 emission intensity	kg CO_2/EUR
RE	GHG emissions intensity	kg CO_2 eq./EUR
RU	Greenhouse gas emissions	Mt (CO_2 eq.)
RU	CO_2 emissions (territorial)	tonnes of CO_2
RU	Carbon footprint	tonnes of CO_2 eq.
EI	Concentration of atmospheric GHG emissions	ppm CO_2 eq.
EI	Change in temperature	°C
Waste and Emissions		
RE	Air emission intensity	kg/EUR
RE	Waste intensity	kg/EUR
RE	Recycling rates	%
RU	Total recycling amounts	tonnes
RU	Total waste generation	kg/year
RU	landfills/art. land	
RU	emissions from landfills	kg
RU	Other air emissions	kg
EI	Exposure of ecosystems to acidification	
EI	Exposure of ecosystems to eutrophication	
EI	Exposure of ecosystems to ozone	
EI	Exceedance of air quality limit values in urban areas	% exceedance

* this indicator was not considered in the RACER evaluation, as not yet existing. The abbreviations "ter." and "res." indicate whether the indicators follow the accounting rules of energy balances and emission inventories (territory principle) or physical energy flow accounts and air emission accounts (residence principle as in the SEEA and input-output analysis).

Other indicators included in the seven indicator sets but not evaluated by RACER:

- Consumption of certain foodstuffs; kg/capita/year
- meat, milk and dairy products consumption, kg/capita/year
- Aquaculture production; tonnes (total production), or tonnes/km of coastal shoreline
- Biotic material productivity; US$/kg
- Abiotic material productivity; US$/kg
- The share of mineral imports in consumption, %
- DMC for non-renewable minerals and fossil fuels; tonnes
- DMI per sector; tonnes
- biomass DE, DMC and DMI; tonnes
- ozone depleting substance use; tonnes of ODS weighted by their Ozone Depletion Potential (ODP)
- production of toxic chemicals; tonnes
- Overall mine production of metals; tons
- Generation and recycling of packaging waste; kg per capita OR percentage
- Total recycling amounts for selected materials; tonnes
- recycling rates for municipal and packaging; %
- Primary energy consumption by fuel; TOE (tonnes of oil eq.)
- Gross inland energy consumption, by fuel; TOE (tonnes of oil eq.)
- Final energy consumption by sector; TOE (tonnes of oil eq.)
- calorie intake per capita; kcal/cap/day
- Energy consumption per m^2 for space heating; GJ/m^2
- total energy consumption for space heating; TOE
- Electricity consumption of households; TOE (tonnes of oil eq.)
- Energy consumption of transport relative to GDP; TOE/€
- acidifying emissions per capita; kg/cap
- Emissions of ozone precursors; ktonnes
- Emissions of acidifying substances; ktonnes
- acidifying emissions per capita; kg/cap
- emission of ground ozone precursors per capita; kg/cap
- Emissions of particulate matter; ktonnes
- air polluting emissions per sector; tonnes
- GHG emissions per capita; kg/cap
- HFCs emissions; gigagrammes
- Status of marine fish stocks; % overfished
- Municipal waste collection; kg/year
- Municipal waste generation; kg/capita/year
- GHG emissions per capita; kg/cap
- CO^2 based productivity; US$ per kg of CO^2
- Greenhouse gas emissions by sector; tonnes CO^2 eq.
- Greenhouse gas emissions by transport mode; tonnes of CO^2 eq.
- Sufficiency of habitat sites; % of sites
- gross nutrient balance; kg N / hectare (/year)
- Agricultural land use by purpose; % of total agricultural land in use
- Forestry land use; hectares
- Bathing water quality; % compliance
- Chlorophyll in transitional, coastal and marine waters; μg/L
- Nutrients in open waters; g/L or μMol/L
- Nutrients in freshwaters; g/L or μMol/L
- Oxygen consuming substances in rivers; BOD (in mg O_2/L) or [ammonium] (in μg N/L)
- Species of European interest; # or percentage of total with specific conservation status by biogeo region
- Global & European temperature; degrees (Celcius)
- Atmospheric greenhouse gas concentrations; ppm CO_2 eq.

- Exposure of ecosystems to acidification; % of total sensitive ecosystem area at risk or Acidifying equivalents
- Exposure of ecosystems to eutrophication; % of total sensitive ecosystem area at risk or Eutrophication equivalents
- Exposure of ecosystems to ozone; % of total sensitive ecosystem area at risk

2. RACER Methodology and Evaluation Results

As the European Commission specified in its publication "Impact Assessment Guidelines" [1], indicators should fulfil the so-called RACER criteria. RACER is an evaluation framework applied to assess the value of scientific tools for use in policy making. The RACER methodology has five criteria, where RACER stands for relevant, accepted, credible, easy and robust:

Relevant *i.e.* closely linked to the objectives to be reached
Accepted e.g. by policy makers and civil society
Credible e.g. regarding methodological transparency
Easy to compile e.g. with readily available data
Robust e.g. in terms of data quality

Applying the RACER framework allows assessing the general value of scientific tools for their use in policy making and providing an indication on the general properties and quality standards of indicators. The RACER framework has been applied in studies on indicators for the Resource Strategy for DG Environment [2,3] and in research projects [4].

In order to specify and operationalize the five very broad RACER criteria, sub-criteria were identified and allocated to each of them. To avoid ambiguous evaluation results, it is important to pose only one specific question for each sub-criterion. Furthermore, in order to support a graphical presentation of the evaluation results, a three-level scoring system was applied, illustrated by colors: green (criterion if completely fulfilled), yellow (criterion is partly fulfilled) and red (criterion is not fulfilled).

The list of indicators (see above) was analyzed regarding the different RACER (sub-) categories. For this purpose, the indicators were grouped regarding the resource group (energy, material use, water use, land-use, carbon and wastes/other emissions) as well as the three perspectives (resource use, efficiency, environmental impact, *etc.*) presented in the article. An indicator completely fulfilling the criterion received the color green (1), a partial fulfilment was colored yellow (2), and red (3) was the color if the criterion is not fulfilled. In the following, we show an overview of the analyzed indicators. Table S2 lists the sub-criteria and related questions as well as guidelines for the evaluator concerning the allocation of green, yellow or red colors.

It is also important to emphasize that the evaluation is undertaken based on the current properties of the indicators, e.g. regarding availability of methodological guideline documents or data, and not with regard to the potential properties, e.g. the potential availability of time-series data in the future.

Table S2. List of criteria for the "RACER" evaluation.

Criterion	Underlying Question	Specification of Criterion	RACER Colour Code
R: Relevant			
R.1: Levels of economic activity	Is the indicator available for the relevant levels of economic activity, *i.e.* countries and sectors?	Data are available on the national and sector level	Green
		Data are only available on either national or sector level	Yellow
		Data are not available on either of the two levels	Red
R.2: Disaggregation of resource components	Does the indicator allow disaggregation of environmental information in the required detail?	The indicator can be used as an aggregated indicator or highly disaggregated into its components to allow specific assessments (e.g. single agricultural products or single metals in material indicators)	Green
		The indicator can be used as an aggregated indicator and be disaggregated into major components (e.g. aggregated land use categories, aggregated material groups, *etc.*)	Yellow
		The indicator is only available as an aggregated number and cannot be detailed for environmental analyses	Red
R.3: Rebound effects	Does the indicator capture rebound effects?	The indicator covers the whole economy and thus captures possible rebound effects on the macro level	Green
		The indicator covers parts of the whole economy (e.g. all manufacturing industries) and thus partly captures rebound effects	Yellow
		The indicator focuses on one specific issue (e.g. one sector, one resource category) and disregards rebound effects on the macro level	Red
R.4: Global perspective/Burden shifting	Is the indicator robust against burden shifting from one country/region to another?	The indicator takes a full life-cycle perspective and is thus robust against shifts between countries	Green
		The indicator includes direct trade (e.g. DMC), but no life-cycle perspective and thus is robust against outsourcing only to a limited extent	Yellow
		The indicator is fully territorial and thus outsourcing improves the apparent performance of countries	Red
R.5: Linkage to issues as scarcity & env. impact		The indicator directly addresses issues such as scarcity or environmental impacts	Green

	Does the indicator link resource use and issues such as scarcity or environmental impacts	The indicator focuses on resource use but allows for a link with issues such as scarcity or environmental impacts	Yellow
		The indicator does not allow for a link with issues such as scarcity or environmental impacts	Red
A: Accepted			
A.1: Policy makers	Is the indicator accepted by European policy makers?	The indicator is accepted and used by policy makers	Green
		The indicator is known by policy makers, but not actively used	Yellow
		The indicators is not considered relevant by policy makers	Red
A.2: Statistics	Is the indicator accepted by statisticians and part of official statistics?	The indicator is accepted and used by statisticians	Green
		The indicator is known by statisticians, but not actively used	Yellow
		The indicators is not considered relevant by statisticians	Red
A.3: Business	Is the indicator accepted by representatives from business?	The indicator is accepted and used by business	Green
		The indicator is known by business, but not actively used	Yellow
		The indicators is not considered relevant by business	Red
A.4: Academia	Is the indicator accepted by academic institutions?	The indicator is accepted and used by academia	Green
		The indicator is known by academia, but not actively used	Yellow
		The indicators is not considered relevant by academia	Red
A.5: Civil society	Is the indicator accepted by civil society organisations, e.g. NGOs?	The indicator is accepted and used by civil society	Green
		The indicator is known by civil society, but not actively used	Yellow
		The indicators is not considered relevant by civil society	Red
C: Credible			
C.1: Transparency of methodology	Are clear specifications of the underlying methodology available (e.g. protocols, standards, technical descriptions), and can the results be easily reproduced?	Full methodological specifications are available in scientifically standardised format	Green
		Methodological specifications are available, but the results cannot be easily reproduced.	Yellow
		No (detailed) methodological specifications are available	Red
C.2: Harmonisation of methodology	Is the underlying methodology harmonised?	Only one methodology exists and is fully harmonised on the international level.	Green
		A few methodological "schools" exist for calculating the indicator (e.g. LCA *vs.* input-output analysis for upstream flows) in parallel. No general consent is reached on which is the best method to apply.	Yellow

		The method available is not approved in a scientifically standardised format.	Red
E: Easy			
E.1: Availability of data to calculate the indicator	How easily can data be obtained to calculate the indicator?	Data is available for free (e.g. internet download) in appropriate formats (e.g. Excel spread sheets; data base formats; vector formats) without restrictions	Green
		Data is available (either in appropriate formats (see above) or formats like pdf or hard copies), but licence systems are applied	Yellow
		Data is not available for third users	Red
E.2: Availability of the calculated indicator	How easily can the calculated indicator be obtained for various users?	The indicator is available for free (e.g. internet download) in appropriate formats (e.g. Excel spread sheets; data base formats; vector formats) without restrictions	Green
		The indicators is available (either in appropriate formats (see above) or formats like pdf or hard copies), but licence systems are applied	Yellow
		The indicator is not available for third users	Red
E.3: Time series	Do time series exist? (and thus allow analysis of historical trends as well as provide input for models of future scenarios)	Data are available for a time series of 10 years or more (or 10 specific years in a longer time period)	Green
		Data are available for a time period of less than 10 years (or less than 10 specific years in a longer time period)	Yellow
		Data are only available for one or two points in time.	Red
E.4: Technical feasibility	Can the indicator be calculated using standard software or does its calculation require specific programmes and technical expertise?	The indicator can be calculated in simple spread sheets without any specific software or specific technical skills	Green
		The indicator calculation requires the use of specific programmes (e.g. LCA software), but the programmes have practical user interfaces	Yellow
		Calculation of the indicator requires mathematical programming skills (e.g. MRIO calculations undertaken with Matlab or similar software)	Red
R: Robust			
R.1: Data quality	How solid is the data quality of the basic data underlying the indicator?	The underlying data is published by national or international (e.g. Eurostat) statistical institutions or international organisations (e.g. UN data units, OECD data units)	Green

		The underlying data is published by academic institutions or other organisations (e.g. business, NGOs, *etc.*)	Yellow
		The underlying data stems from unknown sources or cannot be judged regarding its quality	Red
R.2: Accordance with official statistical/accounting standards	Are the used data and the methodology in accordance with official statistical/accounting standards?	The used data and the methodology are in accordance with official statistical/accounting standards	Green
		Either used data or the methodology are in accordance with official statistical/accounting standards, but differences can be detected in specific aspects.	Yellow
		The used data and the methodology are not in accordance with official statistical/accounting standards	Red
R.3: Share of estimated data	Are the used data to a large extent real or estimated?	Only empirical data from statistical sources or own data compilations are used.	Green
		The used data are to a large extent real.	Yellow
		The data are mainly estimated via estimation procedures or modeling.	Red

2.1. Results of the RACER Evaluation

In the following, we will give a summary of the outcomes of the RACER evaluation with a closer look taken on the results of each resource category, the most relevant indicators and the areas of most significant potential for improvement in order to make the indicators apt for their application in resource efficiency policies.

2.1.1. Energy

For the resource category "Energy", ten indicators were selected for the RACER light evaluation. Three additional indicators were considered relevant for the framework, but skipped from the evaluation, as they do not exist yet. From these non-existing indicators, the indicator "Energy Footprint" deserves special attention, as this is the only one, which would fully consider all up-stream energy requirements. No indicators for the issues of "environmental impacts" or "ecosystem services" were considered in the energy field.

As energy productivity indicator, we selected GDP over Total Primary Energy Supply (TPES) and GDP over Total Net Energy Consumption. The former follows the accounting rules of the energy balances and is the main indicator used by EUROSTAT, although in terms of energy intensity, *i.e.* expressed as TPES/GDP. In contrast, the second one follows the accounting rules of the SEEA (System Environmental-Economic Accounting). The energy productivity indicators are usually presented on the economy-wide level, thus the level of disaggregation is limited, resulting in an aggregated score of 1.8 (yellow) in the "Relevance" criterion. As in the case of DMC (domestic material consumption), energy imports are accounted for in terms of the energy content when they cross the border, not in their primary energy equivalents. Nonetheless, the ratio between the imported energy product and its primary energy equivalent is likely to be much higher than the one between materials imported and its raw material equivalents. In all other RACER categories, TPES/GDP indicator scores well, as its two components are firmly established within the European statistical system. This is not the case for Total Net Energy Consumption/GDP since the denominator is based on energy accounts, which have only been implemented by a few countries and are not well known to all the relevant stakeholders. Nonetheless, EU Member States will have to report energy accounts soon, which will lead to higher scores in future evaluations.

Eight energy indicators were evaluated in the thematic issue of "Resource use". Four indicators refer to absolute levels of energy use, *i.e.* Total Primary Energy Supply (TPES), and Final Energy Consumption (FEC) based on the territory principle, and Total Net Energy Consumption and Total Energy Requirement based on the residence principle. The remaining four indicators link indicators of absolute energy use, *i.e.* expressing the dependency on energy imports, and the share of renewables in total energy consumption. All the indicators generally score well in the "Relevance" criterion and emphasize their importance in a European resource efficiency indicator system. Acceptance of the resident based energy indicators is good in the statistical field, with policy makers and academia. Nevertheless, the residence based indicators score lower because they are relatively new and have not been widely implemented yet. Use of macro energy indicators is very limited in the business area, apart from the energy dependency indicator, which also has direct implications on energy security issues for companies in a country. Energy accounting is a well-established field and EUROSTAT and other institutions (such as the International Energy Agency) publish annual data on various territory-based energy indicators. The indicators that set into relation two different energy indicators, as well as the indicators based on the resident principle are less frequently calculated, however, for the former basic data for their calculation are easily available from the basic energy statistics. Data quality is generally good across all energy use indicators based on the territory principle, resulting in top scores in the Robust criterion. For the reasons mentioned above, this is not the case for the residence-based indicators.

2.1.2. Materials

For the resource category "Materials" for each of the four thematic issues, *i.e.* resource efficiency, resource use, and environmental impacts, at least two indicators were selected for the RACER evaluation. For each issue at least one indicator reached a green evaluation in the relevance criterion (average score lower than 1.5). Only the indicator on fish catches was evaluated with a medium performance (yellow color).

Regarding the issue of "resource efficiency" the indicators which scored best in the relevance (R) criterion were the material productivity indicators "(GDP/RMC raw material consumption)" and "(GDP/TMC total material consumption)". Both take a global perspective and thus avoid misleading conclusions on the economy's material productivity that can occur with GDP/DMC domestic material consumption [5]. However, both indicators with a global perspective score worse than GDP/DMC in the other RACER categories, as the methodologies are not yet as well established and the data availability and quality is lower than with GDP/DMC. GDP/RMC scored slightly better than GDP/TMC in categories, which refer to data quality and availability, in particular as data on unused domestic extraction are still not widely available and of very diverse quality.

In the thematic issue of "resource use", several indicators had an aggregated green evaluation regarding their Relevance (R), *i.e.* the import dependency indicator as well as the indicators on raw material input/consumption and total material requirement/consumption. The indicators on direct material flows (i.e. DMI direct material inputs, DMC domestic material consumption, PTB physical trade balance) scored worse in the R criterion, as these indicators are so far mostly available on the national level only and are not robust against burden shifting, as only direct physical trade flows are covered. The main potentials for improvements regarding indicators on raw material and total material flows can be seen in the level of acceptance by different stakeholder groups, in particular regarding better embedding of these indicators in the statistical system and linking them to issues of relevance for companies. For both RMI (raw material inputs) and RMC as well as TMR (total material requirements) and TMC, various methodological approaches are currently being tested and harmonization still needs to be achieved. Availability of data is also still lower compared to DMC and the TMR and TMC indicators in particular suffer from an insufficient coverage of unused material extraction, which led to a lower score in the "Easy" criterion compared to RMI or RMC.

Regarding the issue "environmental impacts" of materials, the two evaluated indicators EMC (environmentally weighted material consumption) and Macro LCA (the latter developed by JRC) had a similar very good performance regarding their relevance. This is derived from the statement by the Resource Efficiency Roadmap that an aggregated indicator on environmental impacts from resource use shall be integrated on the top level of the EU indicator system once available. The indicator "material use/natural stock" was not evaluated, as it does not yet exist. EMC and Macro LCA perform quite similarly across the other RACER categories. Both are not well established yet and thus lack acceptance with various stakeholder groups. As the two indicators have been proposed by specific groups (EMC: CML/University of Leiden; Macro LCA: JRC/Ispra), the level of harmonization is high, but transparency of the calculations can still be improved. Both indicators score equal in the "Easy" criterion, with the difference that available time series of EMC are currently longer compared to the Macro LCA indicator – although work on time series of the latter is ongoing. Finally, the indicator "Fish catch outside safe biological limits" received an average score (yellow) regarding its relevance for the indicator framework due to its focus on only one category of biotic resources. However, the indicator received very good evaluations throughout the other four RACER categories, as it is well established in the statistical system and available through EUROSTAT.

2.1.3. Water

The evaluation for the resource category "Water" included 10 indicators along the different issues. While three indicators had been selected for each of the issues resource use and environmental impacts, only one indicators was analyzed for resource efficiency issue. While all indicators regarding environmental impacts reached high scores (*i.e.* green with <1.5) within the relevant criteria, only one other indicator was evaluated green in the resource use topical issue. The indicator analyzed for "resource efficiency" got close to it (1.6), while among the "environmental impacts" indicators the WEI+ also received a yellow evaluation (1.6 to 1.8).

Regarding "resource efficiency", for the analyzed indicator (Water productivity (GDP/water appropriation) in almost all the "ACER" categories potentials for improvements were identified. First, regarding the level of acceptance by different stakeholder groups, there is still work to be done to increase the acceptance of the indicator especially by policy makers and businesses, as well as by civil society. Therefore, the water topic has to become more prominent. Also when it comes to "credibility", ratings could be improved by focusing on methodological harmonization and documentation of the same. It has to be agreed upon which indicator to use to quantify "water appropriation" and which level of economic detail to focus on—which will also result in an increase in acceptance. Another consequence of such a focus would be that the indicator would be calculated on a regular basis improving also the availability of time series. In fact, the indicator is not very widely used yet and hence is not too elaborated.

Three indicators were analyzed for the issue "resource use", and—similarly as in the material category—also here the indicator taking the consumption (global perspective) scored best. Thereby, the term "water footprint" is not to be understood as the indicator first published by Chapagain and Hoekstra [6] but refers to the general method of accounting for the water requirements along the whole production chain. The water footprinting concept is already quite accepted among stakeholders; however improved and aligned methodologies would help increase acceptance and credibility. This also relates to its "easiness", as water consumption along the production chain is still difficult to quantify, resulting in a lack of calculated indicators and time series. In this regard, also the data quality still has potential for improvement—as still a large share of the used data is estimated due to confidentiality and other reasons.

Regarding the issue "environmental impacts", three indicators were evaluated, which can be grouped in two groups – the WEI (water exploitation index) and WEI+ (being the advanced form of the WEI taking into account water consumption instead of water use) tackle the topic of water scarcity while waste water treatment is an indicator tackling the topic of water pollution. The WEI (and WEI+) is relevant from the point of view that they compare amounts of water appropriated with the available water resources. While the relevance category "Levels of economic activity" still offers room for improvement (such as disaggregating into watersheds and sectors), the main drawback is its focus on the national level—so, no global (consumption) perspective is taken. Also, with regard to acceptance by business the indicator can "learn" from the water footprint—aspects such as water supply security for economic activities make the indicator relevant for businesses. While both, WEI and WEI+ still lack the availability of data of good coverage and quality, the WEI+ still needs to be further developed and published to increase credibility and easiness.

With regard to "urban waste water treatment", it can be concluded from the RACER evaluation that this indicator is already very advanced. Its lack of relevance (especially regarding the global aspect) is due to its focus on the specific and localized issue of urban water pollution.

Finally, all three indicators relating to "ecosystem services" received the same score. Also here, while analyzing the indicators it was observed that the issue "ecosystem services" does not fit too well in the relevance analysis which is more oriented at the quantitative material use based indicators. The selected indicators overall score very good in the different "RACER" categories. Only "available water resources" shows potential for improvements – especially regarding data availability and data quality.

2.1.4. *Land*

For the resource category "Land" 14 indicators were selected for the RACER evaluation. Among the five topic issues, "environmental impacts" are well represented with 10 indicators that were evaluated. For each other topical issue two indicators were analyzed.

Interestingly, the three indicators, which reached a green relevance evaluation, are all consumption-based indicators, considering burden shifting through trade. Other indicators, highly relevant from an environmental perspective, were certified only medium relevance due to their regional focus and their limited level of sector and resource detail. In particular regarding the topic "ecosystem services and quality", the evaluated indicators gain low scores for the relevance criteria. Highly aggregated data and a missing global perspective, which make a link between biodiversity losses and production and consumption are the main reasons for this result.

The indicators evaluated to be the most relevant (*i.e.* land footprint, ecological footprint and eHANPP embodied Human Appropriation of Net-Primary Production) in comparison show relatively low scores in the easiness and robustness criteria. This is also valid for the indicators related to ecosystem services and biodiversity.

The racer evaluation shows that some of the most urgently needed indicators require high amounts of data from various sources, demand advanced technical skills, and still need further development and harmonization. Some of these shortcomings, however, are potentially insurmountable, and policy makers might be required to deal with uncertainties if some of the most critical issues should be addressed by indicators. This is particularly the case for consumption-based indicators (e.g. land footprint) and for indicators based on complex biophysical modelling approaches (e.g. carbon content in soils).

2.1.5. Carbon

The indicators for the category of "Carbon" contain territorial indicators (*i.e.* CO_2 and GHG emissions and their respective intensities), life cycle based indicators (*i.e.* Carbon footprint) and indicators that are the final result of complex interactions in System Earth (*i.e.* atmospheric GHG concentrations and change in temperature). The territorial indicators by definition cover all emissions of the whole economy within that territory. This means that these indicators cover rebound effects but since they do not take a life cycle approach, they are only partly robust against burden shifting *i.e.* the burden shifting within the territory. The robustness against burden shifting is the main property of the Carbon Footprint indicator. Although temperature change and GHG concentrations can be measured on a local scale they cannot be disaggregated to sectors because they are the result of complex interactions in the global system. At the same time these indicators take rebound effects and territorial burden shifting into account by definition because of their global nature.

Before this background, both indicators evaluated for the issues "resource efficiency" and one indicator for "resource use" scored high with regard to their relevance; also the indicators chosen for "environmental impacts" ("Concentration of atmospheric GHG emissions") and for "ecosystem services" ("Change in temperature") scored just at the threshold for high relevance (1.5 on average).

The two efficiency indicators ("CO_2 emission intensity" and "GHG emission intensity") show a high level of acceptance, but some potential for improvements with regard to their credibility—the transparency and harmonization of the calculation methodology. Both show a strong need for improvement in the RACER categories "easy" and "robust"—hence, a lot of work has to be invested in the improvement of data availability and quality, as well as the availability of the calculated indicators and their accordance with statistical standards.

The issue "resource use" shows one indicator especially relevant for the framework—the Carbon Footprint. It seems that improvements are especially needed concerning its acceptance among statisticians and academia as well as regarding the methodological harmonization and transparency. Also, its robustness ("R") still needs to be improved, especially when thinking about data quality and accordance with statistical standards—which is strongly related to its acceptance.

As explained above, the indicators chosen for "environmental impacts" ("Concentration of atmospheric GHG emissions" and "Change in temperature") scored just at the threshold for high relevance. They show most potential for improvement with regard to their acceptance by stakeholders such as business and civil society.

2.2. Waste and Emissions

For the resource category "Waste and Emissions" for each of the four thematic issues, *i.e.* resource efficiency, resource use, and environmental impacts, at least three indicators were selected for the RACER evaluation. For each issue at least one indicator reached a green evaluation in the relevance criterion (average score lower than 1.5). In the categories "resource efficiency" and "resource use" two indicators were identified as being relevant.

In the category "resource efficiency" the two indicators regarded as relevant are "air emission intensity" and "recycling rates". Both lack the direct link to scarcity or environmental impacts though. Both indicators show a high level of acceptance among almost all the relevant stakeholders. Also, they score excellent with regard to their easiness (availability of data and data series, *etc.*). Potential for improvement can be observed especially with regard to the harmonization of the calculation methodology.

In the category "resource use" the indicators "total recycling amounts" and "other air emissions" were identified as relevant. Also here, both indicators lack the direct link to scarcity or environmental impacts, show high levels of acceptance and have their main improvement potential in the harmonization of the methodology.

With regard to "environmental impacts" the only indicator with a green evaluation in relevance is "exposure of ecosystems to acidification". The main potentials for improvement lie in the transparency and harmonization of the methodology (credibility) as well as in the data quality.

2.3. Summary of RACER Evaluation

The RACER evaluation of the selected indicators highlighted two issues: first, the relevance of an indicator differentiates whether an indicator is already implemented or so far only conceptualized. Second, the RACER evaluation tested whether an indicator has potential for further improvement of acceptability, clarity of methods, easiness of data availability and compilation techniques, and robustness of data quality and the consideration of important issues such as the rebound effect and burden shifting. Indicators might be highly relevant but need further development or there might be good indicators that lack relevance for resource efficiency.

For more details on the RACER evaluation and results see the DESIRE project report D4.2 at http://fp7desire.eu/documents

References

1. European Commission. *Impact Assessment Guidelines*; European Commission: Brussels, Belguim, 2005.
2. Best, A.; Giljum, S.; Simmons, C.; Blobel, D.; Hammer, M.; Lewis, K.; Cavalieri, S.; Lutter, S.; Maguire, C. *Potential of the Ecological Footprint for Monitoring Environmental Impacts from Natural Resource Use: Analysis of the Potential of the Ecological Footprint and Related Assessment Tools for Use in the EU's Thematic Strategy on the Sustainable Use of Natural Resources*; European Commission: Brussels, Belgium, 2008.
3. Mudgal, S.; Tan, A.; Lockwood, S.; Eisenmenger, N.; Fischer-Kowalski, M.; Giljum, S.; Bruckner, M. *Assessment of Resource Efficiency Indicators and Targets. Final Report Prepared for the European Commission, DG Environment*; Contract Number 07.0307/2010/580623/ETU/C1 implementing Framework Contract number ENV.G.4/FRA/2008/0112; BIO Intelligence Service, Institute for Social Ecology, and Sustainable Europe Research Institute: Paris, France, 2012.
4. Wiedmann, T.; Wilting, H.; Lutter, S.; Palm, V.; Giljum, S.; Wadeskog, A.; Nijdam, D. Development of a methodology for the assessment of global environmental impacts of traded goods and services. Available online: www.eipot.eu (accessed on 23 October 2015).
5. Wiedmann, T. O.; Schandl, H.; Lenzen, M.; Moran, D.; Suh, S.; West, J.; Kanemoto, K. The material footprint of nations. *Proc. Natl. Acad. Sci.* **2015**, *112*, 6271–6276.
6. Chapagain, A.K.; Hoekstra, A.Y. *Virtual Water Flows between Nations in Relation to Trade in Livestock and Livestock Products*; Value of Water Research Report Series; UNESCO-IHE Institute for Water Education: Delft, The Netherlands, 2003.