Development of a System of Indicators for a Resource efficient Europe

SEVENTH FRAMEWORK PROGRAMME

DESIRE

Development of a System of Indicators for a Resource Efficient Europe

D10.2 Final report with indicator framework, indicator set and implementation roadmap

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About DESIRE

DESIRE is a FP7 project that will develop and apply an optimal set of indicators to monitor European progress towards resource-efficiency. The project runs from September 2012 to February 2016. We propose a combination of time series of environmentally extended input output data (EE IO) and the DPSIR framework to construct the indicator set. Only this approach will use a single data set that allows for consistent construction of resource efficiency indicators capturing the EU, country, sector and product group level, and the production and consumption perspective including impacts outside the EU. The project will:

- Improve data availability, particularly by creating EE IO time series and now-casted data
- Improve calculation methods for indicators that currently still lack scientific robustness, most notably in the field of biodiversity/ecosystem services and critical materials. We further will develop novel reference indicators for economic success.
- Explicitly address the problem of indicator proliferation and limits in available data that have a 'statistical stamp'. Via scientific analysis we will select the smallest set of indicators giving mutually independent information, and show which shortcuts in (statistical) data inventory can be made without significant loss of quality.

The project comprises further Interactive policy analysis, indicator concept development via 'brokerage' activities, Management, and Conclusions and implementation including a hand over of data and indicators to the EU's Group of Four of EEA, Eurostat, DG ENV and DG JRC.

Partners are:

1. The Netherlands Organisation for Applied Scientific Research (TNO), Delft, Netherlands
2. Wuppertal Institute (WI), Wuppertal, Germany
3. Alpen Adria University - Institute of Social Ecology (UNI-KLU), Vienna, Austria
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Introduction

In this final report of the DESIRE project we convert results from all previous work packages into conclusions, and present results of prioritized indicators that could be calculated with readily available statistical data, and present an indicator implementation roadmap.

Conclusions on the most appropriate Resource Efficiency indicator framework are based on:

- WP4's final indicator framework of WP4 (that builds on WP3's policy analysis and review of existing indicator sets);
- EXIOBASE version 3[1] that has been developed within DESIRE's WP5, with improved data coverage and time series of multi-regional Environmentally Extended Input-Output (EE-IO) tables;
- Results of WP6, WP7 and WP8 on 'novel indicators' (i.e. critical materials, biodiversity/ecosystem services, and novel reference indicators 'beyond GDP');
- and, lastly, results of WP9's statistical analyses on options to reduce the size of the indicator set and options for EE-IO data simplification.

This report also builds on a preliminary draft version that was distributed in the form of a discussion note among participants of the final conference on the 21st of January 2016 in Brussels. Discussions during the conference functioned as last stakeholder consultation round of which the outcomes are taken aboard in the indicator implementation roadmap as presented in the current report.

For details on the full set of resource efficiency indicator results over time, including an annex with EXIOBASE version 3's full classification and available data we refer to Desire Deliverable D9.1, written by Stadler et al. (2016). We do not duplicate this information in the current report, D10.2, for the purpose of making this final project report a more easy to read summary of key results for a wider reader audience.

Acknowledgement
This report is based on contributions of all DESIRE consortium members to previous deliverables.

[1] After a last round of updates, EXIOBASE version 3.2.3 is available since the beginning of February 2016.

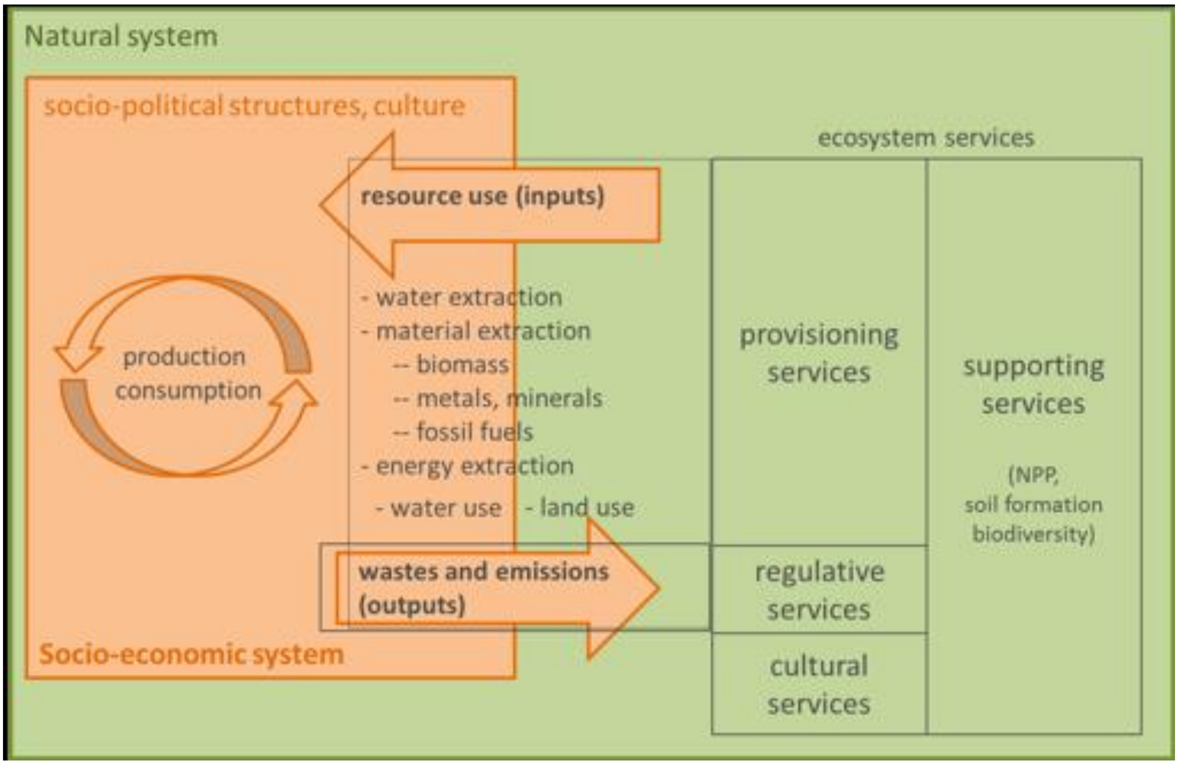
1 DESIRE indicator framework

1.1 DESIRE's conceptual framework

The DESIRE project aims to develop an optimal indicator set to monitor progress towards Resource Efficiency in Europe, yet taking into account the relevant global perspective. Resource efficiency is about *using* natural resources efficiently, either in a technical sense (i.e. less physical input per physical output) or economic/welfare sense (i.e. economic or societal value generated per unit of resource). The latter implies a need to discern all possible interactions between society and the natural system in a coherent and integrated way. The concept of societal or industrial metabolism is helpful in this regard.

This concept refers to the notion that socio-economic systems require resources (materials, energy, water or land) as input in order to produce goods and services or to maintain socio-economic structures. In addition, production and consumption processes, as well as transportation, put a burden on the environment through their (metabolic) outputs such as wastes and emissions to air, water and soil. "Resources" thus address different categories and issues, all with different impacts to "environment", i.e. climate, biodiversity, ecosystems, health, etc. Resource [use] efficiency indicators therefore need to address complex interactions between society and the environment in order to empower political action; to set meaningful targets; and to adequately monitor the [global] use of resources.

Figure 1.1: Society-nature interactions as metabolism

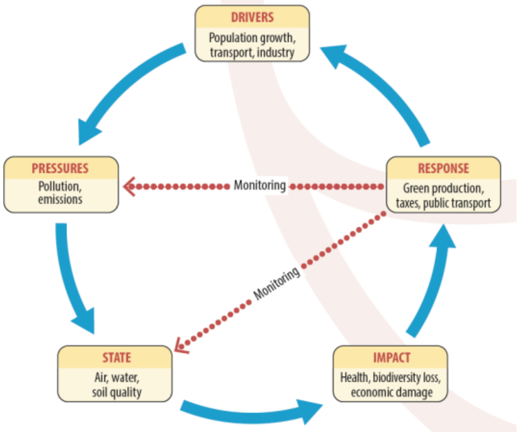


Source: in adapted form taken from Eisenmenger et al., 2016

DESIRE captures these metabolic relations between the natural environment and society, in a framework of Multi-Regional Environmentally Extended [economic] Input-Output relations with production and consumption flows. This [MR EE-IO] framework is referred to as "EXIOBASE".

With this framework it is then possible to assess how production and consumption impacts the natural system. The DESIRE indicator framework builds on the causal Driver-Pressure-State-Impact-Response (DPSIR) frame, adopted by the European Environmental Agency (EEA), to understand society-nature interactions. This framework helps to structure and organise indicators along a cause and effect chain. That is: ***drivers*** for resource use; that put ***pressure*** on the environment; resulting in environmental ***impacts;*** and causes changes in the ***state*** of the natural system. These insights can eventually be a trigger for ***responses*** from relevant ***actors***. Responses that feed back on drivers and thus closes the cycle (see figure 1.2). In the DESIRE project, the DPSIR-framework is integrated with the metabolic perspective of society-nature interactions (see figure 1.3)

Figure 1.2: The DPSIR framework



Source: EEA

Drivers
The structure and characteristics of the socio-economic system, its economic processing, and household consumption patterns are considered driving forces (drivers), which are strongly shaped by the cultural, political, and economic context they are embedded in.

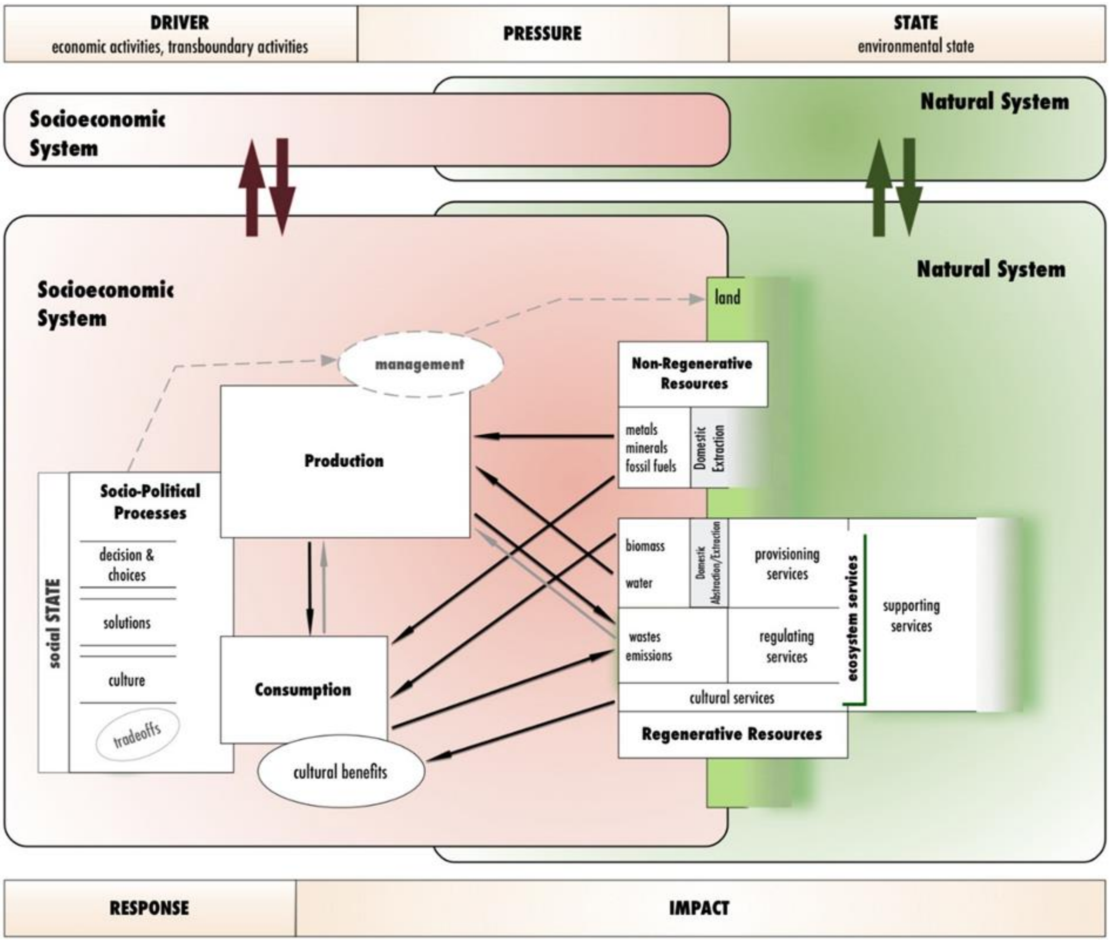
Pressures
Resource use and management activities put pressure on and potentially change the natural system, its ecosystems and ecosystem services and thus the underlying natural *State*.

Impact
Effects of pressures on the natural system are considered environmental impacts. These impacts can, for example, form a threat on human health, human well-being (i.e. a broad concept of welfare) or economic wealth. Environmental impacts could be interpreted or weighted against a certain amount or quality of natural capital stocks, e.g. planetary boundaries.

Responses

Responses are the decisions and choices made within the socio-economic system by individuals or by policy makers as a response to changes in the societal as well as natural systems with the aim to adapt to these. Examples are: tax regulations, legislation or other (thematic) policy response packages.

Figure 1.3: Conceptual framework for DESIRE's indicator set on resource use

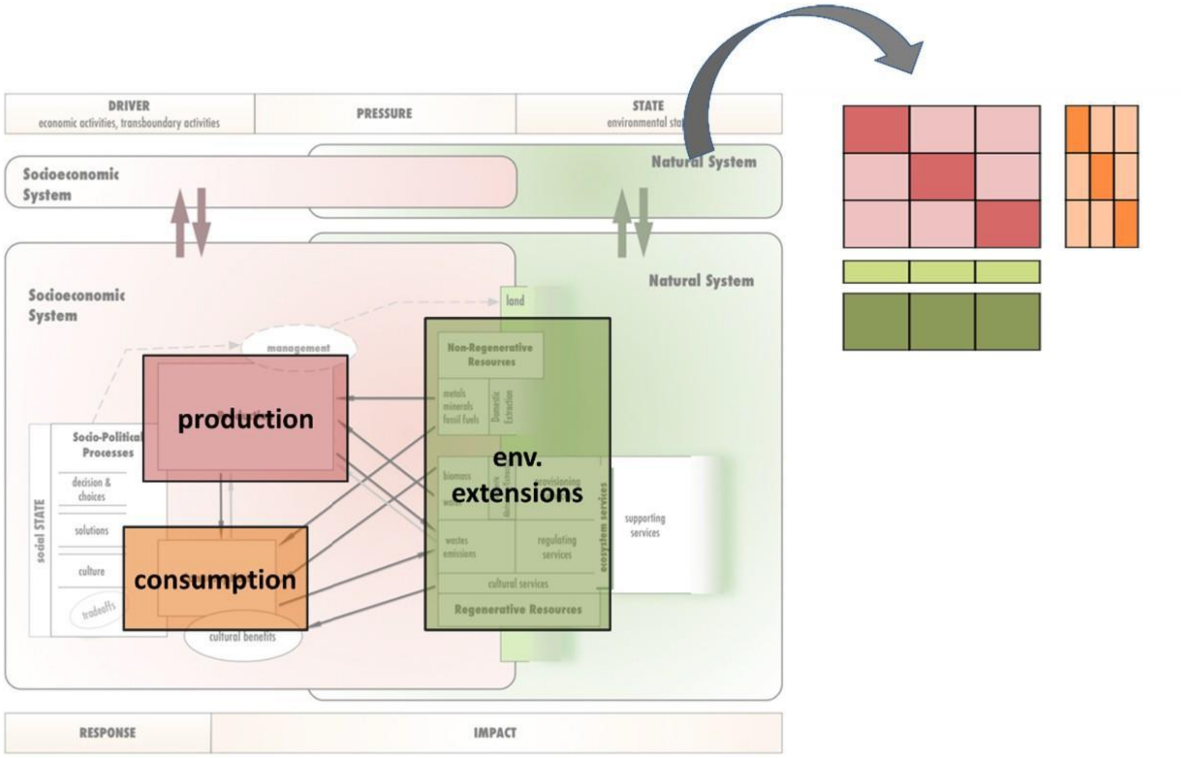


Source: Eisenmenger et al., 2014

The conceptual interactions between socio-economic activities and the natural environment as depicted in figure 1.3 can be integrated in an environmentally extended input-output framework (see figure 1.4).

Input-output (IO) tables originate from economic accounting. Together with its two main building blocks – supply- and use tables (SUTs) – IO-tables form the backbone of the system of National Accounts. Typically, an input-output table includes inter-industry flows in monetary units as well as flows between industries and the final demand categories (e.g. households, government spending, capital investment, exports). By that, IO tables allow for tracing goods from the extraction process through manufacturing and down to final demand and provide information on the inputs needed by an industry to provide the respective industry output. One could say, it supplies the "ingredients" for one unit of output of the manufacturing industries, either derived directly or also indirectly from other industries. From an IO table, the main economic output indicator, Gross Domestic Product (GDP) can be derived. National statistical offices from all around the world provide SUTs and IO-tables, typically at an interval of a few years.

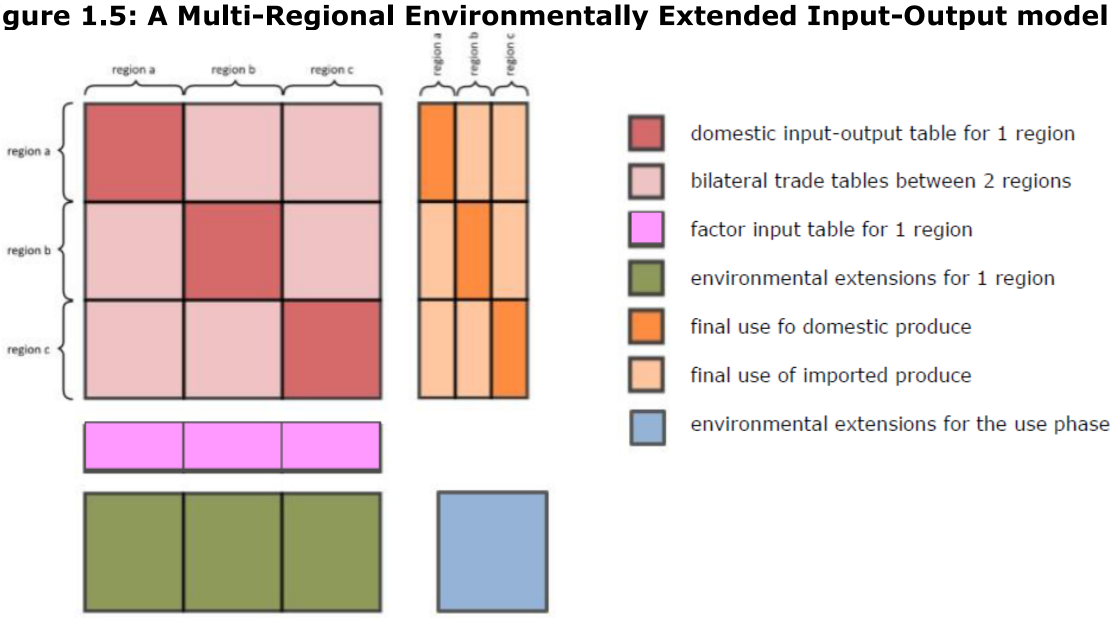
Figure 1.4: Integration of DESIRE's conceptual frame in a MR EE-IO framework



Source: Eisenmenger et al., 2014

The standard economic input- and output flows can be complemented with environmental extensions such as material extraction, land use and emissions to air, soil or water (i.e. environmental pressure indicators). The environmental or natural resource inputs enter the production process of a certain sector and are than further distributed via inter-sectoral deliveries until they end up in one of the final demand categories. Thus, the environmental extensions represent the resource use indicators and data, i.e. pressure indicators in absolute values. Figure 1.5 shows these relations in a multi-regional set-up.

Figure 1.5: A Multi-Regional Environmentally Extended Input-Output model



Source: Eisenmenger et al., 2014

1.2 Complementing and improving EXIOBASE

The indicator framework of DESIRE builds on previous versions of EXIOBASE that were developed with support from the EU's Sixth and Seventh Framework Programmes, i.e. the FP6-project EXIOPOL (that delivered EXIOBASE version 1) and FP7-project CREEA (that delivered EXIOBASE version 2).

EXIOBASE version 1 comprised an extensive economic-environmental database that followed the principles of the System of National Accounts [SNA 1993] and System of Environmental-Economic Accounting (SEEA 2003), based on the International Standard Industrial Classification of All Economic Activities (ISIC and its European equivalent NACE[2]) and Statistical Classification of Products by Activity in the European Economic Community (CPA). EXIOBASE version 1 provides data for base year 2000.

Accordingly, in the CREEA project, the database and indicator framework was refined according to the new accounting approaches of SNA 2008 and those that were proposed for inclusion in SEEA 2012 regarding four priority areas: water, waste and materials, forestry, and climate change issues.

Version 2 of EXIOBASE provided data at an at an unprecedented level of detail in terms of sectors, products, emissions and resources with coverage of 43 countries; 27 EU countries and the largest non-EU economies (summing up to 95% of the global GDP) with over 150 smaller countries combined in 5 'Rest of the World' groups by continent. EXIOBASE version 2 provides data for base year 2007.

Moving-on from here, DESIRE complemented and improved the database with new statistical information and expanded the indicator framework by adding the 28th EU Member State, Croatia, and by compiling time series, including now casting of recent years for which not all data is available yet from official statistical publications. With these improvements EXIOBASE version 3 can now be used to analyse consumption and production based accounts as well as stressors embodied in imports and exports, including developments over time.

EXIOBASE version 3 has the following characteristics:

EXIOBASE 3	
Base-years	**1995 – 2011/16** *)
Products	**200**
Industries	**163**
Countries	**44** (28 EU member plus 16 major economies)
Rest of the world regions	**5** (Europe, Asia, Africa, America, Middle East)
Water accounts	**194** (Water blue and green per source, including final demand)
Material accounts	**189** (Energy products, including final demand) **222** (Used extractions) **222** (Unused extractions)
Land accounts	**14** (Including build up land for final demand)
Social accounts	**14** (Employment per skill level and gender; vulnerable employment)
Emissions	**28** (from combustion including final demand) **410** (non-combustion) **3** (HFC, PFC, SF6)

*) Historic time series for up to 2011, the rest of the years has been now-casted.
Source: Stadler et al., 2016

[2] Nomenclature of Economic Activities, used by the European Statistical Community.

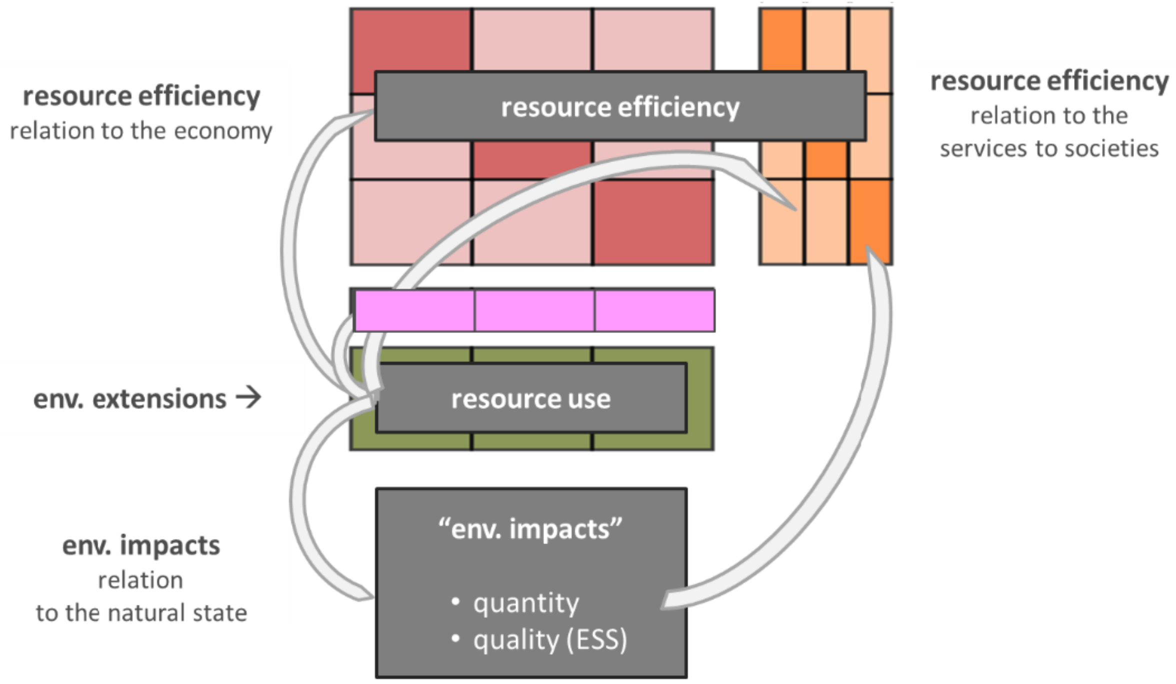
1.3 DESIRE'S Resource Efficiency indicator framework

DESIRE's indicator framework differentiates three main categories of indicators: *resource use*, *resource efficiency* and *environmental impacts* (the columns in table 1.1 below). In addition the framework comprises six flow types of resource inputs or (metabolic) outputs (as indicated by the rows in table 1.1). In accordance, figure 1.7 shows how these Resource Efficiency indicators are positioned in the multi-regional EE-IO model.

Table 1.1: Environmental indicators in the DESIRE indicator framework

	Resource use	Resource efficiency	Environmental impact
Energy Materials Water Land Carbon emissions Wastes and other emissions	*Monitoring of absolute flows*	*Measurement of "productivity", e.g. per € of output*	*Assessment of quantity and quality of stocks*

Figure 1.7: Positioning of Resource Efficiency indicators in the EE-IO model



Source: Eisenmenger et al., 2014

Pressure indicators, related to direct society-nature interactions, i.e. **resource use indicators** in absolute physical terms, are a good starting point to measuring resource efficiency. These are input flows of materials, energy, water and land to intermediate use and final use in the IO-framework, as well as output flows thereof of waste and emissions.

Accordingly, resource use has to be complemented by indicators that capture the effects on the natural system (impact indicators) as well as effects on the socio-economic system. The latter are commonly referred to as **resource efficiency indicators**. In DESIRE's indicator framework two types of resource efficiency indicators are distinguished: resource efficiency indicators *in relation to the economy* and resource efficiency indicators *in relation to services to society*.

Resource efficiency indicators in relation to the economy (production and consumption based) can be measured against GDP or value added, and hence directly be linked to economic transactions in the IO-framework. Efficiency indicators in relation to services to society, on the other hand, often need (detailed) auxiliary data from sources outside the IO-framework. Services to society concern functional outputs rather than economic outputs, such as adequate housing, space heating, nutrition, etc. By their nature these outputs have a 'beyond GDP' connotation and can sometimes best be expressed on a rather micro level. An example of such a resource efficiency indicator is the required energy consumption for space heating per m^2 of dwelling floor space. In the DESIRE project a work package was devoted to test opportunities for using novel reference indicators 'beyond GDP and value added'.[3]

The third main indicator category in the DESIRE framework, **environmental impacts** of resource use, put socio-economic pressures in relation to the natural state, and inform about both quantitative and qualitative aspects of natural capital stocks. They can inform about the state of stocks and changes thereof over time, e.g. depletion, degradation, climate change, biodiversity loss. For these type of indicators a satellite account of natural capital stocks need to be connected to the IO-framework. This is the lower block of data indicated in figure 1.7.

Table 1.2 summarises the rationale behind the indicator types and their position in the DPSIR-framework. It covers the pressure indicators in absolute values (columns in yellow) as well as the "resource efficiency" indicators (columns in yellow as well) which result from relating resource use to macro-economic added value (e.g. GDP) or macro-economic well-being indicators. The columns on the left cover the socio-economic system. Additionally to the resource efficiency indicators that link to socio-economic macro indicators, resource efficiency can be analysed as the relation between resource use and specific societal services provided (column in red). This covers all the activities that directly deal with biophysical flows, however no longer structured along the macro-economic IO matrix but along societal services. The socio-political responses (column in pink) cover the social, political, economic, or cultural responses.

[3] Because this is one of the more 'experimental' research efforts of DESIRE, results of this work package are described in a dedicated section of chapter 2 on development of 'novel indicators'.

Table 1.2: DESIRE indicator types and their position in the DPSIR-frame

Source: Eisenmenger et al., 2014

The green columns on the right side cover the efficiency of resource use in relation to the environmental impacts on the natural system in two dimensions, quantitatively and qualitatively. These environmental impacts are structured along the commonly used environmental threats (boxes on the very right). Thus, the environmental impacts do not follow the IO structure, just as the socio-economic activities at macro level.

The general idea behind DESIRE's indicator framework is to apply a 2-level system: a limited set of headline indicators that covers resource use, resource efficiency and environmental impacts on the macro (i.e. country) level, and an accompanying second level of indicators addressing specific questions within each category.

1.4 A set of readily available Resource Efficiency indicators

EXIOBASE contains the physical layers *energy*, *water, materials* and *land*, which can be tracked as resource inputs to the economic production process. In addition there are various material extions that provide information on metabolic outputs of production and consumption processes, such as emissions and waste. EXIOBASE covers:

- Greenhouse gas emissions, in kilograms of CO2, CH4, N2O;
- Polluting emissions: SOx, NOx, NH3, CO, Benzenes, Indeno (1,2,3-cd) pyrene, PAHs, PCBs, PCDD_F, HCB, VOCs, PM10, PM2.5, TSP, As, Cd, Cr, Cu, Hg, Ni, Pb, Se, Zn, SF6, HFCs, PFCs);
- Nitrogen and phosphorous emissions to water;
- Domestic material extraction of various types of crops, wood, metal ores, industrial and construction minerals & fossil fuels (differentiated in used and unused extracted materials);
- Withdrawal of blue water, differentiated by the manufacturing, electricity production and domestic use sector;
- Green and blue water consumption, differentiated by use category, for various types of agriculture, livestock, manufacturing, electricity production and domestic consumption;
- and land use (by different types of arable land, pastures and forests).

Of the full set of possible indicators that are directly calculable from EXIOBASE, some might score differently on criteria that are relevant for their uptake and implementation in policy making or for monitoring purposes, i.e. on so-called RACER-criteria: *Relevance, Acceptability, Credibility, Easiness and Robustness.* The proposed indicators in the 2-level indicator system are therefore tested along the lines of these RACER-criteria. The results of this exercise are shown in Annex 1, indicating the relevance of indicators and possible needs for further development. Table 1.3 (below) provides a sample of indicators that can directly be calculated.

From IO-tables coefficients of industry requirements in monetary terms can be calculated (i.e. direct requirement coefficients and Leontief multipliers). Similarly, these factors can be calculated for environmental impacts at two levels of detail:

Scope 1: Direct environmental interventions

Direct environmental interventions (for example, air emissions or material extraction) are available for each industry without further calculations from the table of environmental extensions (i.e. the dark-green boxes as shown earlier in figure 1.5 and the "resource use part" in figure 1.7). One can sum the extensions for all industries in the region, plus the interventions reported under final use (= use phase interventions), to derive the country total. Scope 1 is a territorial perspective, expressing environmental consequences, which originate within a country's or region's territory.

Table 1.3: Examples of environmental indicators calculable with EXIOBASE

Topic	Indicator name	Definition/Unit
Energy	Energy dependency	import/total use (%)
	Primary energy intensity	ktoe/euro
	Energy use (total net energy consumption) by fuel	tons of oil eq.
Materials	Material productivity	€ per kg Domestic Material Consumption € per kg Raw Material Consumption € per kg Total Material Consumption
	Import dependence	Imports/Domestic Material Consumption (%)
	Domestic Material Consumption	tonnes
	Raw Material Consumption	tonnes
	Total Material Consumption	tonnes
Water	Water productivity	€ per m^3
	Water abstraction	m^3
	Water consumption	m^3
	Water footprint	m^3
Land	Land productivity	€ per ha
	Artificial land / built-up area	hectares
	Land Footprint / Actual Land Demand	hectares
Carbon	CO_2 emission intensity	kg of CO_2 per €
	GHG emissions intensity	kg of CO_2 equivalent per €
	CO_2 emissions	tonnes of CO_2
	GHG emissions	tonnes of CO_2 equivalents
	Carbon Footprint	tonnes of CO_2 equivalents
Waste and emissions	Air emission intensity	Kg emission per €
	Waste intensity	Kg waste per €
	Recycling rates	%
	Total recycling amounts	tonnes
	Total waste generation	tonnes
	Emissions from landfills	tonnes
	Emissions of air pollutants	tonnes

Scope 2: Total (direct plus indirect) environmental interventions

The main advantage of IO-models applied to environmental issues is that they allow calculating the total direct plus indirect effects for all products and all sectors, also those with very complex supply chains, as the whole economic system is included in the calculation system. IO-analysis thus avoids so-called "truncation errors" often occurring in coefficient-based approaches, i.e. errors resulting from the fact that the whole complexity of production chains cannot be fully analysed based on Life Cycle Assessment (LCA) approaches, where as a consequence certain up-stream chains have to be "cut off". IO-analysis thus avoids imprecise definition of system boundaries, which is one key advantage over other approaches. IO-models also avoid double counting, as different supply chains are clearly distinguished from each other in the monetary input-output tables. Thus, a specific resource input can only be allocated once to final consumption, as the supply and use chains are completely represented.

However, IO-analysis also contains some disadvantages. Whereas LCA-type approaches are able to cover both upstream and downstream environmental effects, IO accounts only for upstream inputs to the production processes and ultimately to final consumption. Environmental consequences from the use-phase are only given in a single table entry, at the intersection of the final use column and the environmental extension row (see the blue square in the lower right corner of figure 1.5). For CO_2 emission for example, this single number includes many types of direct emissions like those from private car use or the emissions related to heating our homes and drinking our soft drinks. Hence, typical use-phase oriented indicators, such as the "per capita CO_2 emissions from the housing and infrastructure sector" (i.e. part of the EEA core set of indicators) are difficult to derive from IO tables directly. In order to calculate these indicators, the vector of private consumption would need to be split up by consumption categories, for example following the COICOP classification, which disaggregates consumption by purpose (e.g. food, housing, transport, communication, etc.).[4]

It shall be emphasised that EXIOBASE is different from other MRIO databases (such as GTAP or EORA) because it contains physical layers at the industry level. Therefore, EXIOBASE contains data on direct physical imports and exports, which allow calculating material flow-based indicators, such as DMC, which would not be possible to calculate with other MRIO systems without physical layers. It also contains detailed waste data, which allows calculating specific indicators, such as recycling rates.

1.4.1 Results of resource efficiency indicators over time

For a full set of resource efficiency indicator results over time and details on underlying data and documentation of all readily available indicators we refer to the report of Stadler et al, 2016 (Desire deliverable D9.1).

We would like to stress that working with DESIRE's MR EE-IO framework and indicators involves a large amount of data, such that some programming skills are required to analyse the detailed datasets. For the purpose of easing these analyses an open source tool, Pymrio, has been developed.[5] This tool has been used to calculate production and consumption based accounts for each stressor per product and per country.[6]

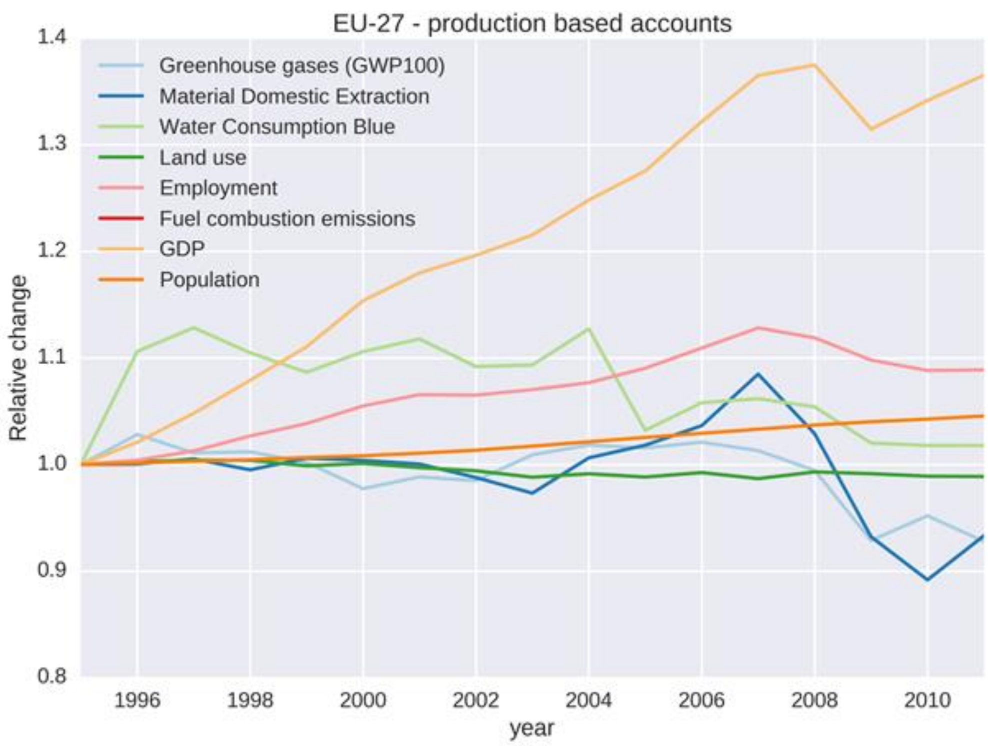
These results can for example be used to assess decoupling of economic growth from environmental pressures. Doing such an analysis for the EU 27 countries shows that, taking a production based account, the European Union appears to have achieved decoupling (see figue 1.8 top). Taking, however, the consumption based perspective (figure 1.8 botom), material usage and fuel combustion grow in the same rate as the economy. In addition, CO_2 emissions, water use and land use are only recently decoupled from economic growth.

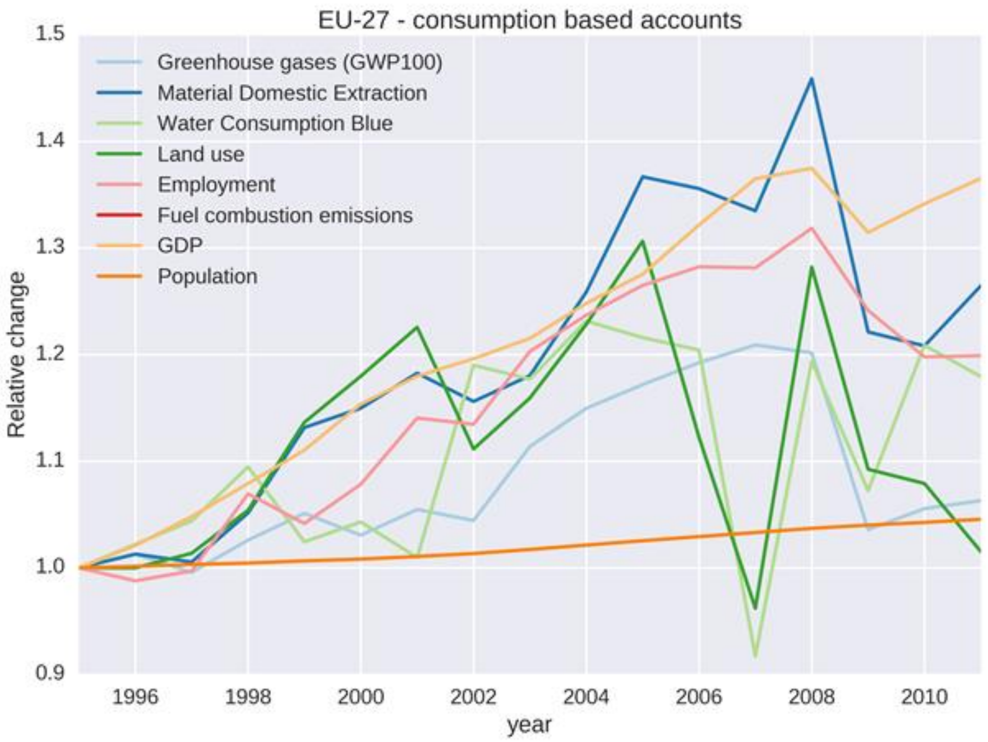
[4] Results of DESIRE's research efforts in these areas will be more elaborately described in a chapter 2 on development of 'novel indicators'.

[5] a full documentation plus tutorials are available on github:
https://github.com/konstantinstadler/pymrio
http://konstantinstadler.github.io/pymrio/index.html

[6] All calculated results are available as csv files on the project repository and can be directly imported in common spreadsheet software. In addition, a html summary report showing the consumption and production based accounts as well as stressor embodied in import and export are provided. All datasets are available upon request for services of the European Commission and will be published after the end of the project.

Figure 1.8: Time series of production- (*top*) and consumption based accounts (*bottom*) of the European Union.
Indicators show the resource efficiency as impact per capita.





Source: Stadler et al., 2016 (calculations based on EXIOBASE v3.2.3)

2 Indicator development: novel indicators

DESIRE aimed to push the state of the art for EE MRIO compilation and calculations. For that purpose, besides developing approaches for now-casting EE MRIOs (see Stadler et al., 2015), DESIRE's research efforts also focussed on more experimental indicator development. This included efforts to develop or improve resource efficiency indicators in the domains: Critical Materials, Biodiversity and ecosystem services, and Novel reference indicators 'beyond GDP', as well as efforts to linking them to the MR EE-IO framework. In general, linking *pressure*s to *state* and *impacts* in these fields proved to be complex sometimes, as it involved manifold or non-linear relations. This made determining causal relations between society-nature interactions and final environmental impacts to the least 'challenging'. In this chapter we report the key results per each of the three, what we call 'novel indicator' domains, and explain the extent to which these results could be linked to the EE-IO framework.

2.1 Critical material indicators

Modern society depends upon a reliable supply of a wide spectrum of different materials. Some important minerals or raw materials in that spectrum have an increased risk of supply shortage due to resource exhaustion or trade barriers, and these are called critical materials. Examples of critical materials include indium, tantalum, or rare earth metals. To assess whether a material is critical or not we need to understand both its importance for society and its supply risk. Critical materials are typically used in small quantities in particular applications (Halada et al., 2008).

Around the world, various studies have tried to define the concept of material criticality. The volume of work, assembled by academia, NGO's and specialist with another background on critical materials, shows that studies on critical materials indicate very different materials to be critical because of at least three reasons:

- their regional focus may be different;
- their methods may differ i.e. using different criticality factors (e.g. some studies do not incorporate environmental impacts or expected future demand);
- their outcomes may only be applicable in different timeframes, because the criticality factors that are used are highly variable.

Following the same structure as for the other 'novel indicators', we first report the indicator conceptualization and methodology and report the results and discussion in a second subparagraph.

2.1.1 Indicator conceptualization and methodology

The objectives of DESIRE’s work package on critical material indicators (WP6) were to specify and define a number of relevant critical material indicators and to link these to the IO-framework. Regarding critical material indicators, economy wide aggregated indicators as proposed in DESIRE’s ‘core’ indicator framework, are not suitable as most of the energy, water, land, carbon and other emissions indicators do not refer to the criticality problem of materials. In addition, the indicators on waste and materials in DESIRE’s indicator framework are on a still too aggregated level to signal criticality problems of material substances as fraction of products. After the first stage of DESIRE’s research activities on critical materials the following indicators were considered relevant:

For the extraction phase
- Critical material footprint (by material or group of materials per country.
- Supply concentration (if possible as used by Graedel et al., 2012)
- Annual production compared to the economic reserves
- Overall material loss (over the extraction phase)

For the production phase & product demand
- Development of the critical material composition per product (gram/product as an efficiency indicator)
- Dissipative use ratio (dissipative use over use in recoverable products)
- Apparent consumption by material (economy wide)
- Material demand growth index
- Total value of products containing a specific material (in order to better estimate the economic importance, one of the criticality factors)
- Overall material loss (over the production phase)

For the use-phase & disposal
- Societal stock build-up
- Ownership rates of different appliances (driver related indicator)
- Value involved in critical material flows over total expenses (allows for a better calculation of the economic importance too)

For the wastes/recycling treatment
- Recycling vs. total waste generation ratio’s
- Waste stream composition
- End-Of-Life recycling rates for specific materials
- ratio of primary vs. recycled material use

For the purpose of linking critical material indicators to the IO-framework different methodologies to assess socio-economic metabolism and their particular suitability to assess criticality of materials were reviewed first. A central methodological aspect of DESIRE’s WP6 was to explore whether monetary and physical multiregional supply and use tables and the derived MR-IO models are suitable tools for the quantification of flows of critical materials and indicators for material criticality.

It was suggested to pursue an approach based on material flow assessment, linked with input output (IO) tables. Furthermore, it was proposed to develop a link between IO-tables and elaborate waste statistics, which are highly relevant for quantifying recycling options. It was concluded that a hybrid mixed unit (i.e. combined physical- and monetery

information) model is in principle suitable for modelling the flows of critical materials in a MR-IO framework, and to determining flow-based resource efficiency indicators. However, at the same time it was acknowledged that availability of data could be problematic to accurately build such a hybrid IO-model. Research efforts in DESIRE therefore also focussed on possibilities to overcome data challenges.
There are numerous challenges involved with connecting material flows and critcality assessments to economic accounts. Some of the most practical challenges are:

- The detailed industrial production, Europroms statistics (PRODCOM), do not distinguish between primary and secondary commodities (or the items are difficult to classify as such). Moreover, the Europroms statistics seem to be poor in monitoring waste and scrap flows.
- Incompatibility between IO-tables from the System of National Accounts and data on material flows. This problem is most apparent when one tries to connect detailed Substance Flow Analysis (SFA) to the product and sector classifications of input-output tables (the latter are often much more aggregated). Other incompatibility issues arise around: unit of measurement (kg of substance vs. monetary units), coverage of stocks (which are absent in IO-tables) and continuity over time of the model (the IO table being strongly bound to an annual set-up).
- A specific challenge with critical materials is to specify quantities of materials in specific products and accordingly to bridge these to the product classification of supply- and use- or input-output tables. In fact, large uncertainties are introduced by the need to have more detailed information on the critical material content in (most often non-ferrous metal) products. Not only is this information rarely available, also several conversions between monetary and physical layers and assumptions of homogenous products have to be made.

As proof of concept for the 'dynamic Technology-Hybridized Environmental-Economic Model', several case studies have been conducted within DESIRE's work package on critical material indicators. The scope of the substance flow analysis case studies was for practical reasons limited to the regions "EU27" and the year "2007". Case studies are performed for Tantalum (Ta), Indium (In), Neodymium (Nd) and several steel alloying elements Chromium (Cr), Manganese (Mn), Molybdenum (Mo) and Vanadium (V). All these case studies had the same sequence of methodological steps (see figure 2.1).

In order to derive critical material flows through Europe the EUROPROMS statistics (EUROSTAT Prodcom statistics) are used to first determine the apparent consumption of critical material-containing ores, materials and products. Secondly, a review of critical material concentrations in those products is performed. Combining these data and performing some additional data processing steps yields the apparent consumption of critical material in various European ores, materials and products, which were then categorized into production stages to result in a highly detailed flow-diagram of critical material in raw materials, semi-finished products as well as in products for final consumption (i.e. "Sankey diagrams"). The scope of the case studies within DESIRE's WP6 was limited to the compilation of Sankey diagrams, meaning that the research activities in the various cases stopped at step 11 as depicted in figure 2.1.

It is acknowledged, however, that as next steps the apparent consumption of end uses of critical materials in products can be used as input for a waste assessment model. With this model it would be possible to assess the expected future critical material recycling potential from consumer wastes by assuming Weibull life-time distributions.

Figure 2.1: methodological steps applied in DESIRE's critical material case studies

Source: Van Oers et al., 2015

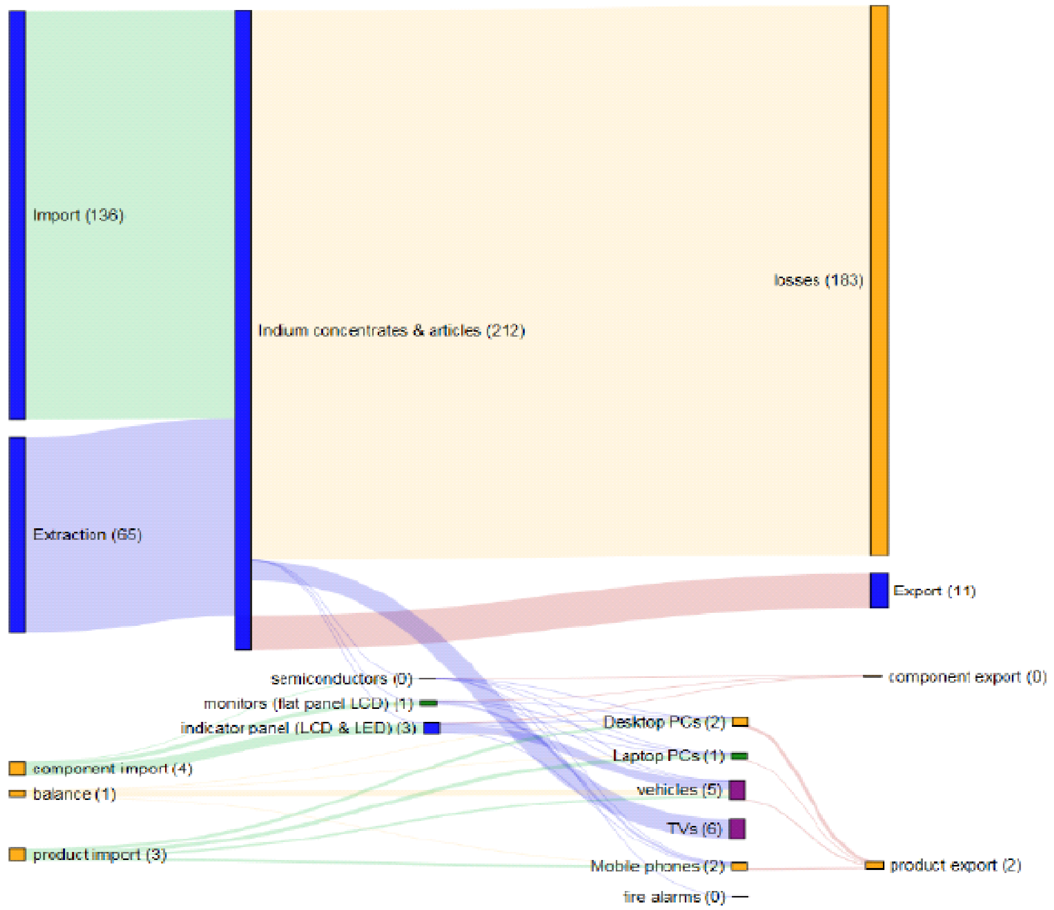
The results of the case studies (i.e. the Sankey Diagrams) for Indium, Tantalum and Neodymium are shown in the next subsection.

2.1.2 Results and discussion

Indium

Figure 2.2 shows the imported flows (in light-green), the exported flows (in light-red), and the intra-European flows of Indium (in light blue). It shows the cascading of the consumed Indium in raw material form (in the blue bars) through the demand for sub-components (in green) and final products (where the colored bars indicate different categories). Careful interpretation is required, as the size of the bars as well as the indicated volumes for each product indicates the size of the Indium flow through Europe (imports, exports + intra EU inputs), so not its actual consumption. The actual consumption of raw materials and sub-components is represented by the light-blue flows.

Figure 2.2: Indium
Annual Indium flows through the EU27 in 2007, expressed in tons Indium. In the Sankey 'extraction' refers to 'production of raw material' (like ores, concentrates, articles including powder, waste, scrap).



Source: Van Oers et al., 2015

Far more indium seems to be mined together with zinc ore than necessary to fulfil the present demand of indium in products.
The loss of indium between production of indium (during mining, smelting and refining) and application in (semi)products (particularly spattering) is about 90% (183t out of 200t apparent consumption), meaning that much of the refined indium does not end up in products.

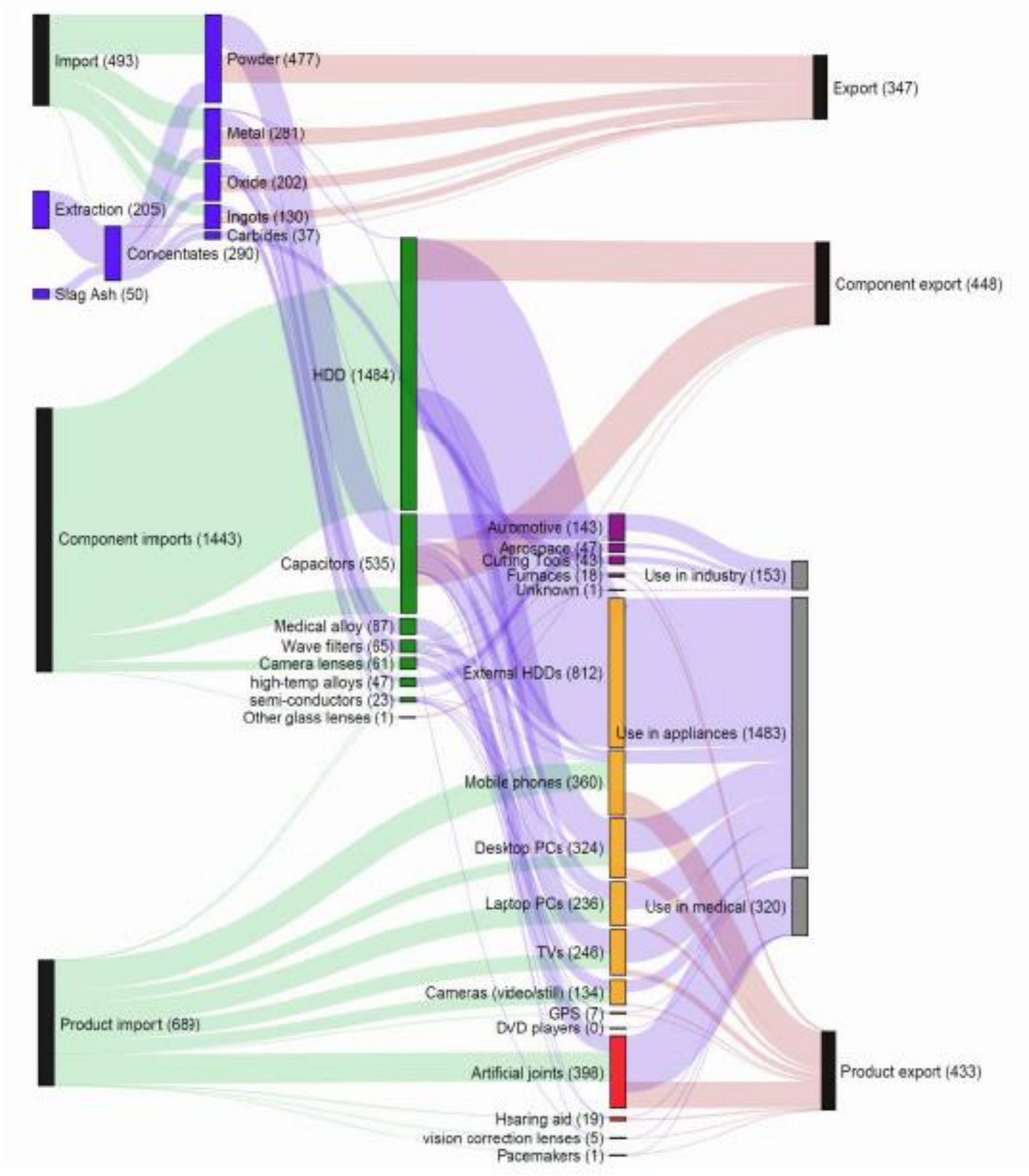
The amount of indium available in final products consumed in the EU27 in 2007 was about 15t (most notably in the category TVs and other final products; the application of indium in LCD screens is most dominant). These figures indicate that the largest potential of recovery of indium is available in wastes from raw material production and not in the recovery of discarded end-of-life products.

Tantalum
Figure 2.3 shows the imported flows (in light-green), the exported flows (in light-red), and the intra-European flows of tantalum (in light blue). It shows the cascading of the consumed tantalum in raw material form (in the blue bars) through the demand for sub-components (in green) and final products (where the colored bars indicate different categories). Careful interpretation is required, as the size of the bars as well as the indicated volumes for each product indicates the size of the tantalum flow through

Europe (imports, exports + intra EU inputs), so not its actual consumption. The actual consumption of raw materials and sub-components is represented by the light-blue flows. The resulting apparent consumption of final products is separately indicated using the grey bars in the lower-right corner.

Figure 2.3: Tantalum

Annual Tantalum flows through the EU27 in 2007, expressed in tons tantalum. In the Sankey 'extraction' refers to 'production of raw material' (like ores, concentrates, articles including waste/scrap).



Source: Van Oers et al., 2015

The overall apparent consumption of tantalum in Europe in final products is much larger than expected based on the total global consumption of concentrates. In fact, the European consumption is twice the global consumption of concentrates as reported by the USGS. This may have two reasons, either this study used assumptions leading to a too high estimate for the tantalum concentration in products, or it may indicate that the real volume of tantalum consumed is much larger than reported, which is not unlikely, given that tantalum is not traded on official spot markets and sourced from conflict areas.

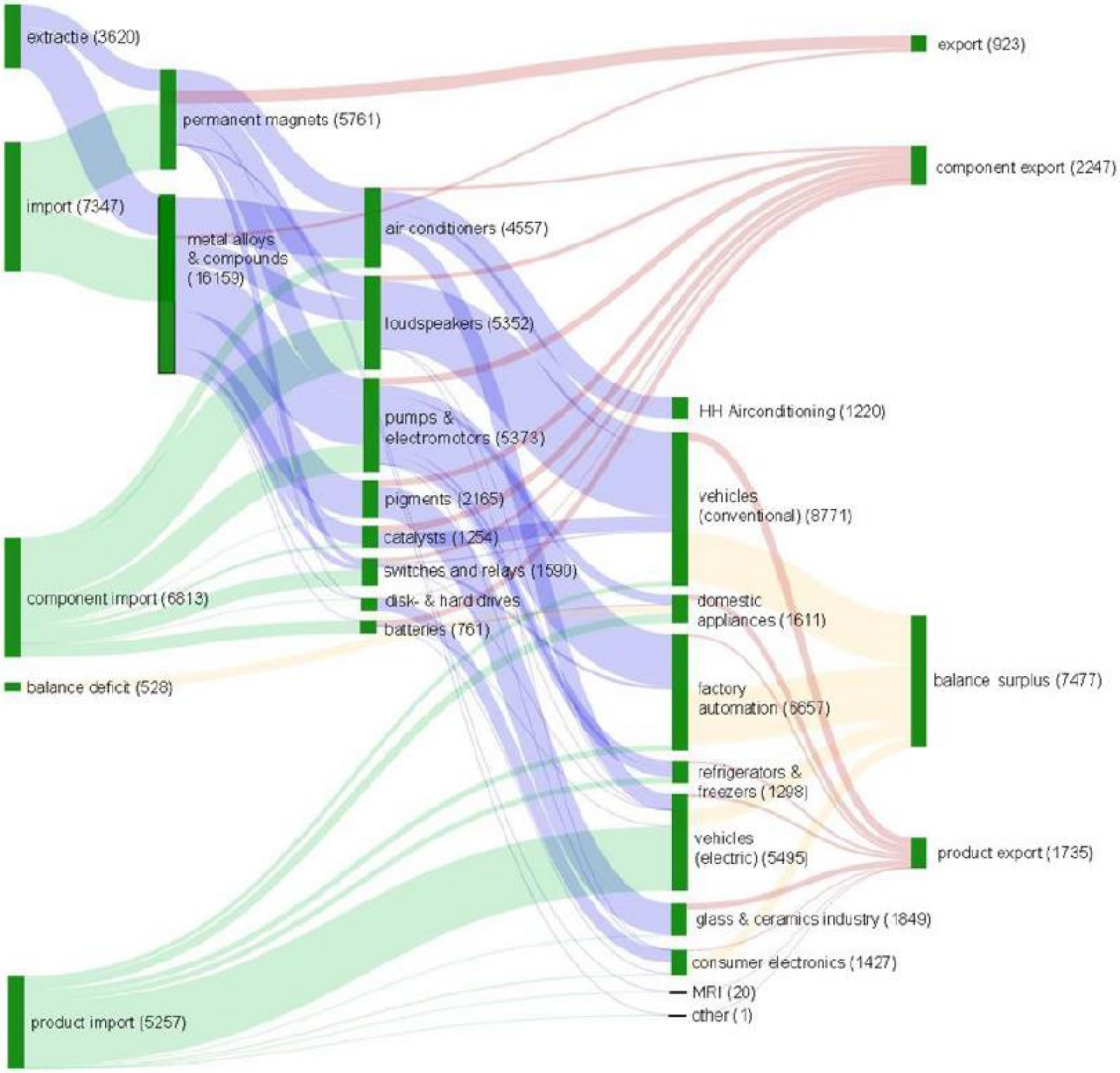
One of the items that stands out in our analysis is the large consumption of tantalum in hard disks for storage of digital data. This is a category that has only been mentioned in one of the qualitative studies investigated in the DESIRE case study, and never as a crucial product. However, the results of our study indicate that hard disks are responsible for 537t of tantalum, when assuming a tantalum content based on a patent (Hitachi, 2007) and an X-ray based composition analysis (Tunney et al., 2011) for consumer-type hard disks using a perpendicular recording mechanism.

Our study is the first to our knowledge to highlight such a high importance of tantalum in hard disks, thus indicating a direction for further research. Another interesting finding is the relatively high importance of tantalum in artificial joints. Though the assumption on tantalum concentration for this product category is based on a selection of medical materials in a single source (Zardiackas et al. 2006).

Neodymium

Figure 2.4 shows the imported flows (in light-green), the exported flows (in light-red), and the intra-European flows of neodymium (in light blue). It shows the cascading of the consumed neodymium in raw material form (in the blue bars) through the demand for sub-components (in green) and final products (where the colored bars indicate different categories). Light orange flows indicate a balance deficit or a balance surplus. Careful interpretation is required, as the size of the bars as well as the indicated volumes for each product indicates the size of the neodymium flow through Europe (imports, exports + intra EU inputs), so not its actual consumption. The actual consumption of raw materials and sub-components is represented by the light-blue flows

Figure 2.4: Neodymium
Annual neodymium flows through the EU27 in 2007, expressed in tons neodymium. In the Sankey 'extraction' refers to 'production of raw material' (like rare-earth metals, compounds, permanent magnets).



Source: Van Oers et al., 2015

A comparison of DESIRE case study results with absolute numbers shows that in 2008 (the closest reference year available), the global consumption of Nd3O2 was 23,900 tonnes, amounting to 22,227 tonnes of pure Nd. In our case study, the consumption of Neodymium in final products is 9,473 tonnes. Since this would amount to about 43% of world consumption, it seems that an overestimation was made of the concentration data or market shares of Neodymium products. On average for all REOs, the EU-27 accounts for less than 8% of world consumption (Polinares, 2012). However, because not much detailed studies focused on the supply chain of critical materials, also the consumption of neodymium in previous studies might be underestimated.

Discussion

Within the DESIRE project, a methodological framework is developed to derive cradle-to-gate Substance Flow Analysis (SFA) from existing Eurostat statistics, Europroms (Prodcom). The framework is operationalized and tested for several selected critical materials. The first results look promising but should still be considered preliminary, given the level of uncertainty of the outcomes. Based on the Europroms statistics and the applied assumptions for concentrations and allocation of (aggregated) Europroms commodities to specific critical material applications there appear to be off balances between the different stages of the material life cycle, raw material, intermediate material and final product.

Scientific robustness and data quality will determine if the development of EE IO frameworks is strong enough to match SFA in terms of acceptability and feasibility. Europroms statistics (Prodcom) seem to enable future indicator use, but many challenges remain: e.g. raw material definitions, euro/kg/unit conversions, concentration of actual material in products, secondary flows.

A big challenge, particularly because of the effect of uncertainties on the outcome, remains the value chains. The first step to improve SFAs is to gather additional information on the internal relationship between the commodities as reported by Europroms. This is necessary to avoid double counting when aggregating commodities.
Finally, when off balances are minimalized after reconciliation of data and allocation factors a calibration step still might be necessary to make balances fit. This calibration step should be reported transparently and calibrated concentration and allocation factors should, if possible, be confirmed with data from literature.

2.2 Biodiversity indicators

2.2.1 Indicator conceptualization and methodology

Ultimately, the aim with DESIRE's indicator framework is to show the impacts that environmental stressors cause. To do so, the stressor results need to be characterized into various impact categories. One separated set of characterization factors was setup for assessing the impacts on biodiversity and ecosystem service functions. The research efforts in DESIRE focussed on the impacts of land use on biodiversity. In Marques et al. (2015), based on a literature review, it is explained that land use change is currently one of the main drivers of biodiversity loss in terrestrial ecosystems. Habitat loss and habitat degradation affect more than 80% of globally threatened mammals, birds, amphibians and plants.

Within DESIRE's work package on biodiversity, three indicators have therefore been developed which can be coupled to the EE MR-IO framework:

(1) Bird species lost;
(2) Cumulative extinction risk of carnivorous mammals; and
(3) Carbon sequestration foregone.

The development of these indicators was dependent on spatially explicit information of land use by sectors included in EXIOBASE. That is because impacts on biodiversity and ecosystems can be very location specific (for example clearing a km^2 of Amazon forest will represent very different impacts on biodiversity than clearing a km^2 of an agricultural field). For the characterization of pressures the production and consumption accounting scheme from the MR EE-IO tables is used.

For each of three indicator types we summarize the conceptualisation, methodology and key results in the next subsections.

Bird species lost

Methodology

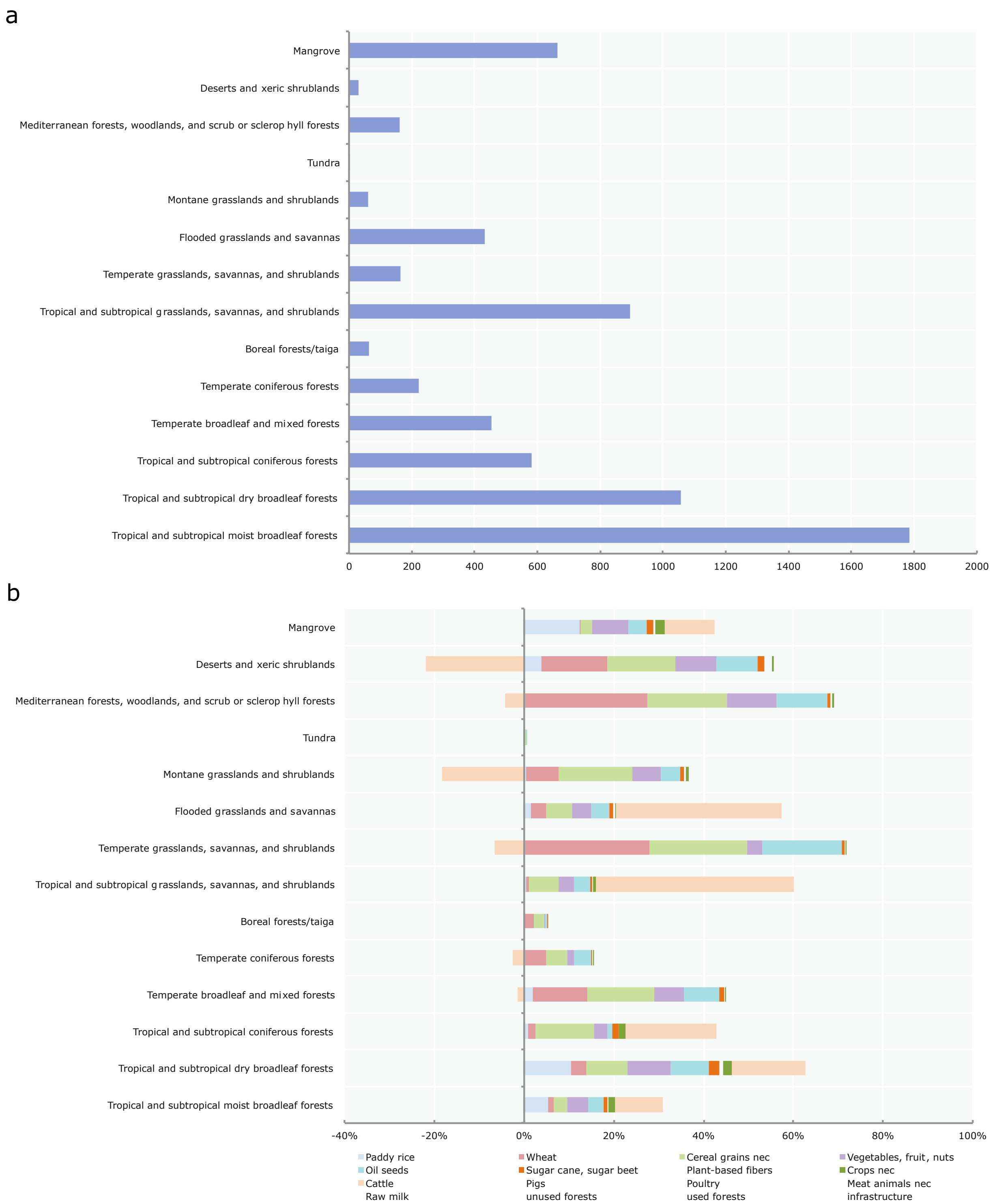
The countryside species-area relationship (SAR) is used to model the total species loss associated to each individual land use sector, both for total species and for endemic species at biome scale, and for total species at grid scale. In accordance geographic range data is used to estimate the real number of species lost in each biome or grid cell. The species loss is then allocated to sectors in each country by taking into consideration the area occupied by each of the 16 land use sectors in a particular biome or grid cell. This is brought in relation to the affinity of bird species to that particular type of land. The 16 land use sectors are the different agricultural and forestry as well as infrastructure sectors shown in figure 2.5, part b.

Three metrics have been developed: *global extinctions* (endemic species loss per biome), *regional extinctions* (species loss per biome) and *local extinctions* (species loss per grid cell). These metrics provide different type of information that is relevant to determine the impacts of different economic sectors on biodiversity. The average of species lost in all grid cells of a country, due to each land use activity, enables building a local biodiversity loss extension to an input-output model like EXIOBASE.

The methodology can in principle be used for all animals provided that relevant and good quality data is available. In DESIRE bird species distribution data from BirdLife International (BirdLife International and NatureServe, 2014) for 10.061 birds species was used. Besides the availability of good quality data for birds, another, more pragmatic, reason to focus only on birds is that they are well studied in terms of their sensitivity to different forms of land-use change. The impacts of land use on biodiversity are calculated at the regional level per biome, as well as at the global level averaged per grid cell or per country.

Results

Figure 2.5: Impacts of land use changes on biodiversity at the regional scale
a) Total number of bird species lost per biome and
b) contribution of each land use sector to the total species loss in each biome.

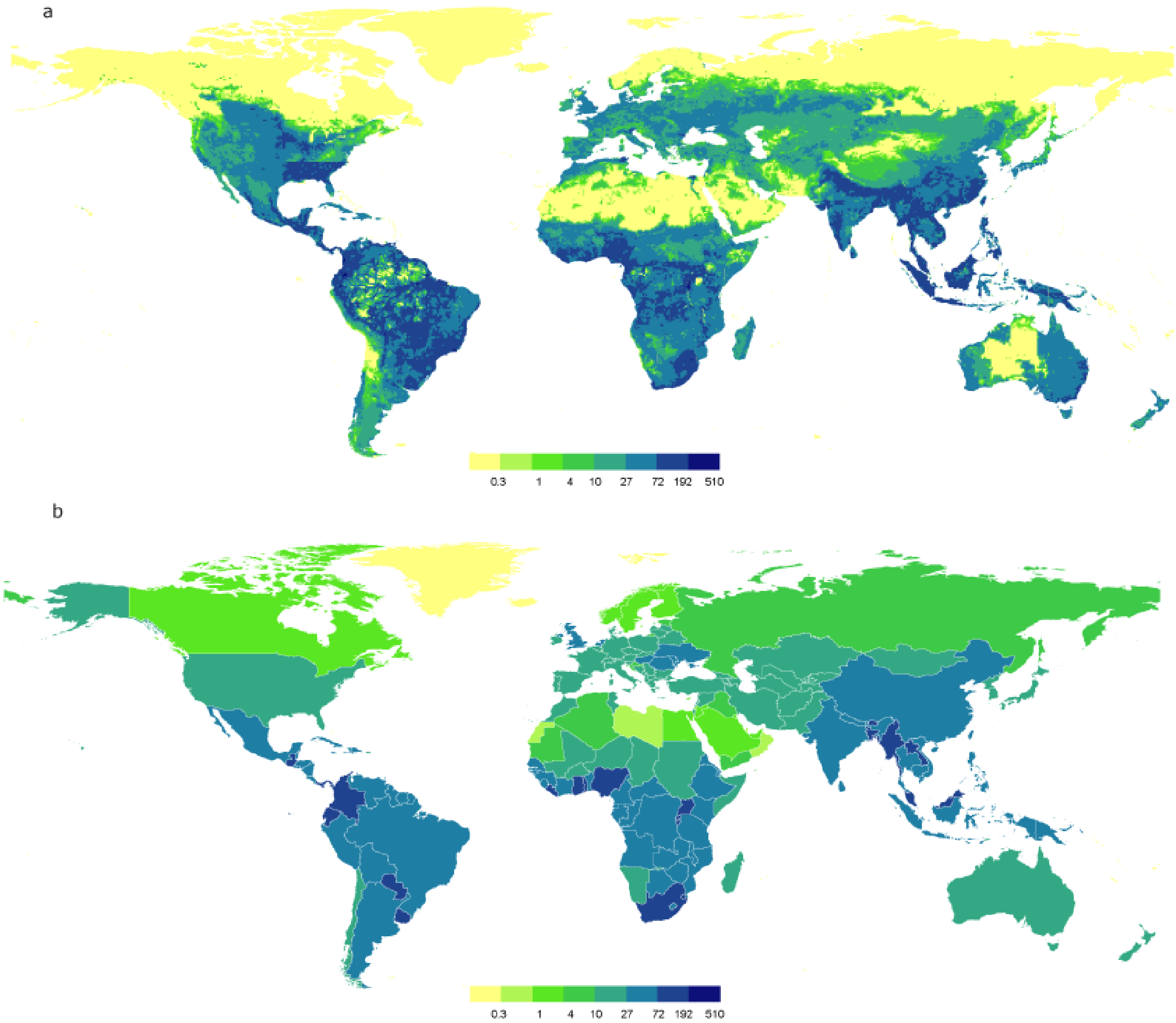


Source: Marques et al., 2015

It is observed that biomes with highest percentages of species loss tend to be also the biomes with higher diversity of endemic and specialist species. The conversion of native habitat to human-modified habitats is predicted to have caused up to 67 global extinctions in tropical and subtropical moist broadleaf forests.

The areas with higher species richness are the areas where more local loss of bird species due to land use activities occur (Figure 2.6a). The average of species lost in all grid cells of a country, due to each land use activity, enables building a local biodiversity loss extension to an input-output model (Figure 2.6b).

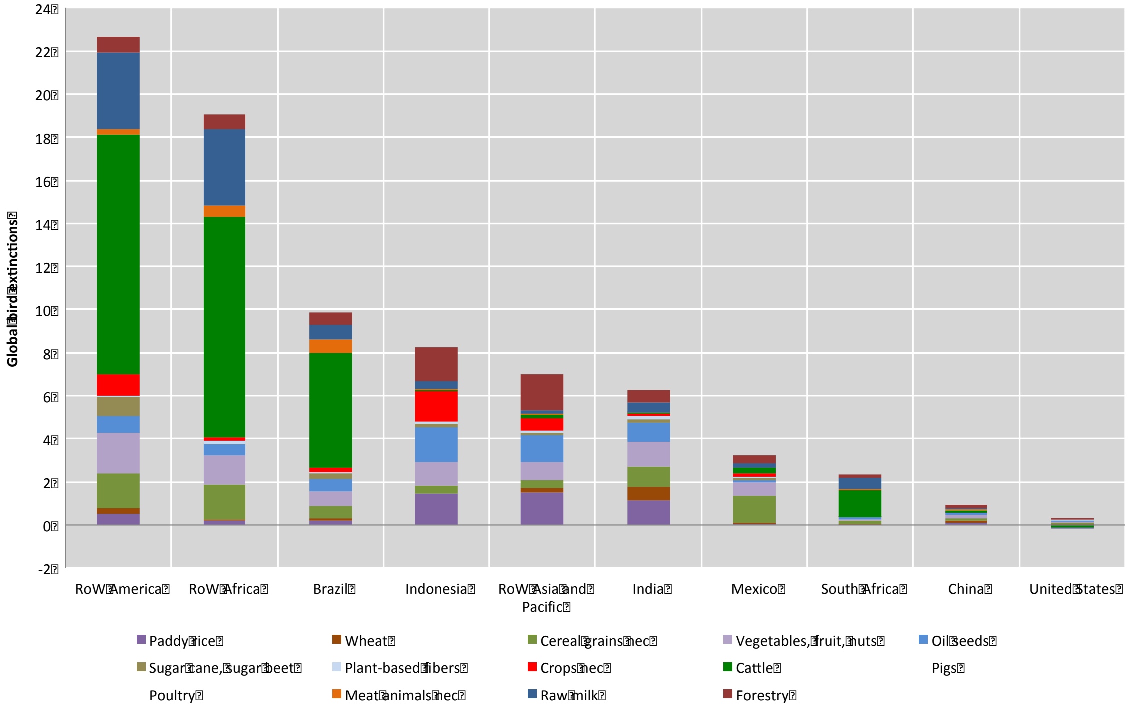
Figure 2.6: Total number of local bird species lost due to different land use sectors
a) results per grid cell, and b) country average of species loss per grid cell



Source: Marques et al., 2015

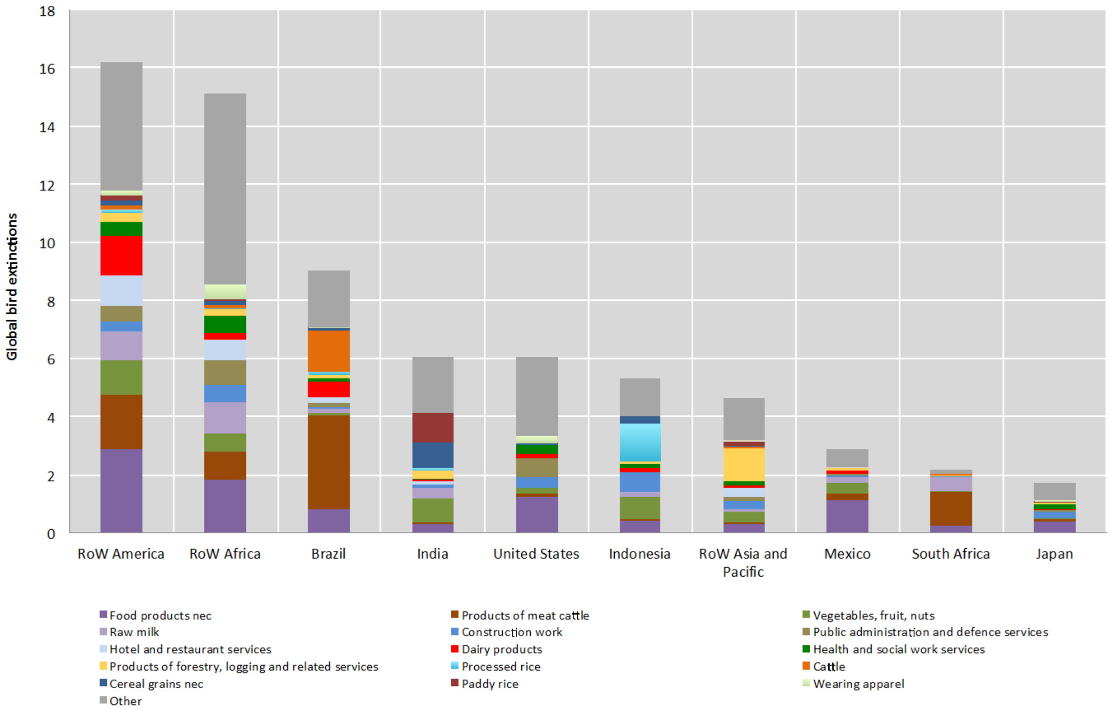
Comparing production and consumption schemes shows that, in general, developed countries are responsible for a major part of biodiversity loss outside their territory. This is due to a relatively high land use, in particular for agriculture, in species rich biomes of South American and African countries, together with high imports of agricultural products to e.g. the US. See for example the difference in bird species extinctions due to [agricultural] production in the US (fig 2.7) and the number of bird species lost due to consumption in the United States (figure 2.8). In addition, figure 2.9 shows how trade, for instance from 'Rest of the World' (South)America and Indonesia to the United states, influences the level of global bird species loss. These results are a clear example of how EXIOBASE can give insights in global value chains of [agricultural and forestry] products, and regional concentration of environmental impacts [in this case bird species loss].

Figure 2.7: Top 10 countries/regions in number of bird species extinction from a production perspective



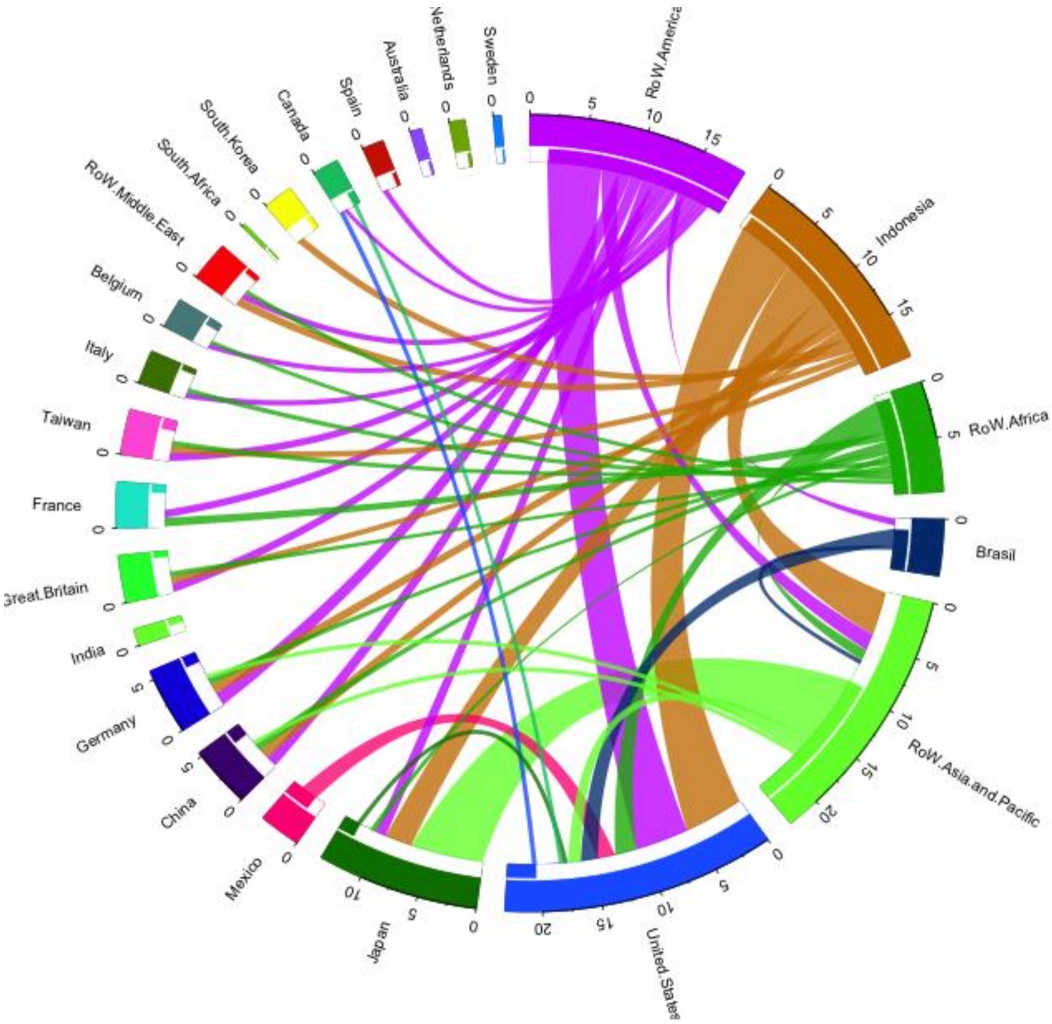
Source: Marques et al., 2015

Figure 2.8: Top 10 countries/regions in number of bird species extinction from a consumption perspective



Source: Marques et al., 2015

Figure 2.9: Global extinction of birds expressed as impact of international trade



Source: Marques et al., 2015

Extinction risk of carnivore mammals

Methodology

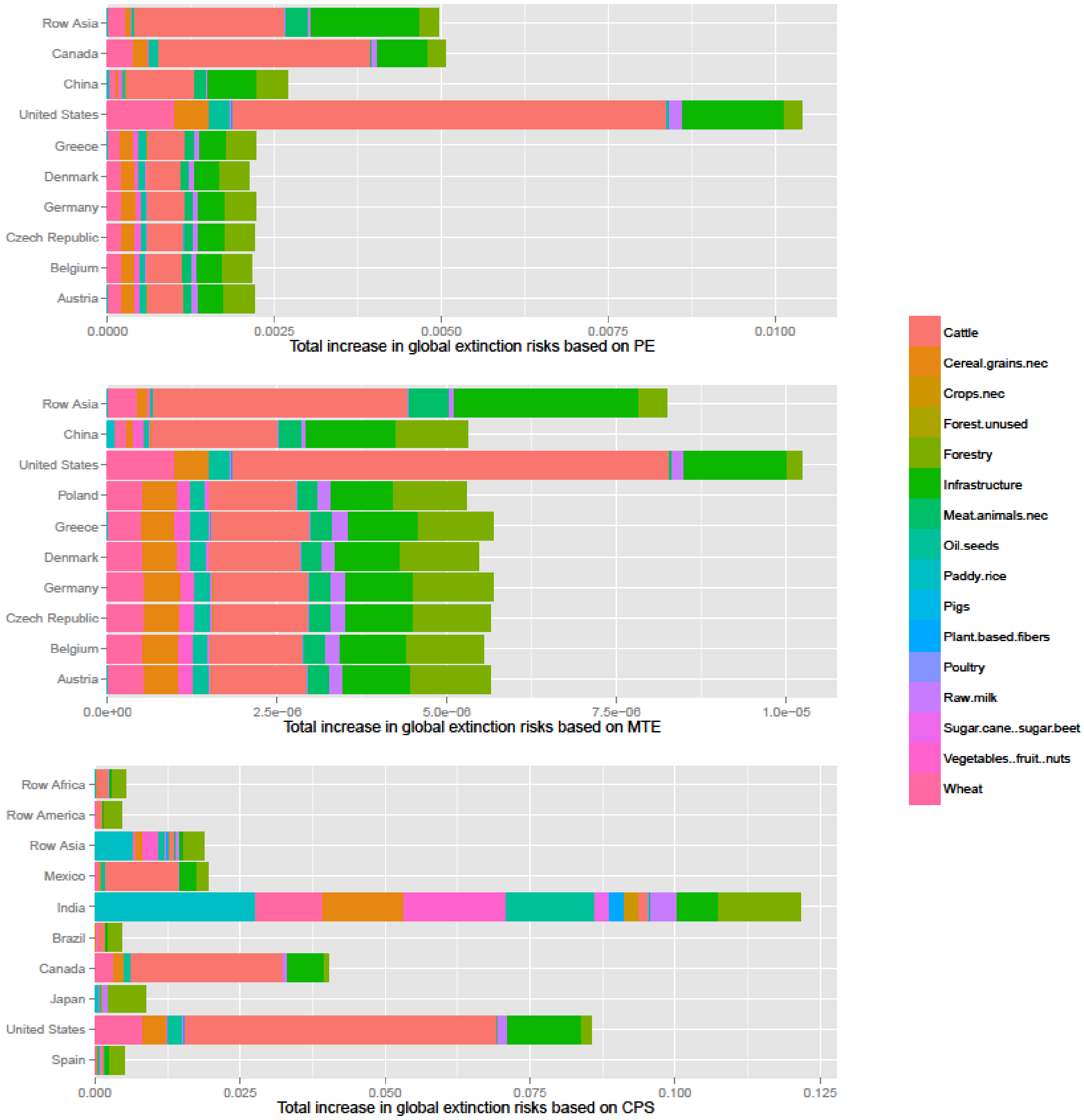
Land use change is said to be affecting at least 40% of all terrestrial mammals worldwide (Visconti et al., 2011). In DESIRE a novel method to calculate the cumulative Extinction Risk Potential (ERP) based on Population Viability Analysis is used to provide insight into the impact of land use change on biodiversity. The ERPs assess the land use change effects of 16 land use sectors on 148 carnivorous mammal species in 46 countries or regions in which the species occur. The developed methodology could in principle be applied to all species, countries and land use sectors if data is available.

As considerable differences were found between countries or regions, the impact of land use should not be quantified at global scales but rather at a country or ecoregion level. In addition, differentiation between land use sectors is important as sectors have different impacts on extinction risk of mammals. The findings suggest that, in case of limited data availability, one should at least between the broader land use categories: forestry, livestock and crop production. The developed ERPs provide a unique means, in combination with environmentally extended input-output models, to investigate how consumption and production structures of countries affect the global extinction of species. However, additional and more detailed data on land use, species-specific life-history characteristics, their habitat preferences and occurrence range are needed to improve accuracy of the assessments.

Results

The total increase in extinction risk due to land use activities was found to vary spatially. Figure 2.10 shows the top 10 countries with highest increase in extinction risks due to land use change for the three indicator metrics used (i.e. *Probability of Extinction [PE], Mean time to extinction [MTE]* and *Critical Path Size [CPS]*). Although differences in extinction indicators exist, all indicators show that carnivorous mammals occurring in the United States and Asia are relatively impacted most by land use change.

Figure 2.10: Top 10 countries or regions with highest increase in extinction risk (ER) with differentiation by land use sectors.



Source: Marques et al., 2015

Carbon sequestration forgone

Methodology

Links between biomass-harvest flows and their impact upon carbon sequestration and the integration of global and national consumption-based accounts into the ecosystem service framework were explored. This resulted in a measure for the impact of land use on regulating services, namely the annual amount of carbon sequestration forgone due to land use. To arrive at this metric carbon stocks of the potential natural vegetation are compared with the actual situation for different land use types.

This first explorative calculation focussed on cropland only, looking at wheat, rice and the sum of all crops in particular. We assumed that in absence of human land use, vegetation would grow back to 75% of the potential natural Carbon-Stock value within 50 years (based on Houghton, 2003).

The firsts explorations showed that calculating a forgone carbon sequestration matching EXIOBASE's regional and sectoral resolution is possible, albeit presently only for the year 2000. The resulting metric could prove useful for linking efficiency measures with impacts of agriculture on regulating ecosystem services, namely carbon storage.

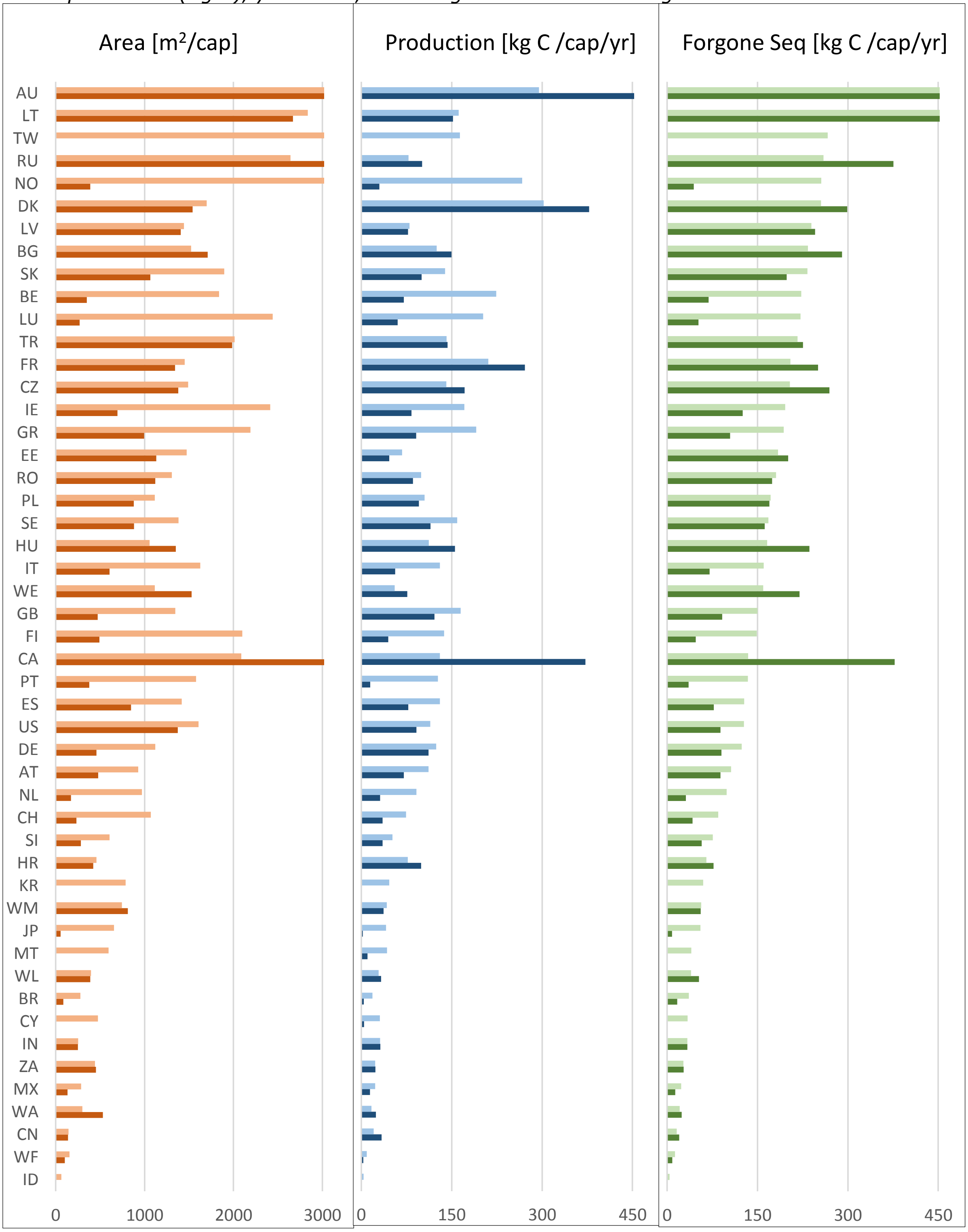
Next development steps, to arrive at a robust full-fledged account of this measure would be: expanding the calculations for other types of land use, namely grazing lands and forests (this includes considering carbon stocks of the present vegetation, which could be neglected for cropland); fine-tuning the temporal dynamics of vegetation recovery in different world regions; and exploring the role the inclusion of fallow lands and multi-cropping has on the results.

Results

Figure 2.11 shows detailed results at the regional level for wheat, respectively ranking the regions from highest per capita value of consumption-based account for forgone Carbon sequestration to lowest. These first results reveal some interesting differences when looking at forgone Carbon sequestration compared to values for area and production. For instance, Russia produced about 60% of the volume of wheat that has been produced in the US in 2000, while inducing about 220% of the forgone carbon sequestration caused by the US production.

In the consumption-based accounts, per capita values are dominated by rich countries. For instance, an average Austrian induced over three times the forgone carbon sequestration due to rice production of the average Indian, and over 9 than the value of the average Chinese person (not shown in figure 2.11 as it only include results for wheat)

Figure 2.11: Foregone carbon sequestration by country
Per capita values for area (left), production (center) and carbon sequestration forgone through wheat production (right), year 2000, according to the EXIOBASE regions.



Darker colors refer to production-based (= territorial) accounts, lighter colors to consumption-based (=footprint) accounts. Note that very high values are "cut off".
Source: Marques et al., 2015

2.3 Novel reference indicators beyond GDP

DESIRE's work on novel reference indicators started from the acknowledgement that GDP and value added are not bad indicators for economic output as such, yet not always sufficiently connected to the input of natural resources and outputs in relation to services to society, i.e. a broader perspective on welfare. Resource efficiency 'beyond GDP' requires a link between natural resources (as input) to human well-being (as output). A challenge is than that 'quality of life' or 'human well-being' aspects have no one-to-one relation with production and consumption. There are much more, and more complex, relations to take into account.

Consumption of goods and services is only one of many mechanisms that contribute to human well-being. It is therefore crucial to acknowledge that the backbone of DESIRE's indicator framework, the MR EE-IO model, focusses on environmental aspects of economic production and consumption transactions only. As for the part consumption is relevant to consider in a broader welfare context, there are no straightforward ways to linking consumption expenditures to human need satisfaction. Moreover, because consumption of a single product or service can satisfy several human needs at the same time. Another limitation of assessments through an IO-framework is that it represents flows in a single year, while past investments or changes in quality and quantity of stocks of different types of capital are important determinants for some aspects of human well-being, such as health or nature's recreational values.

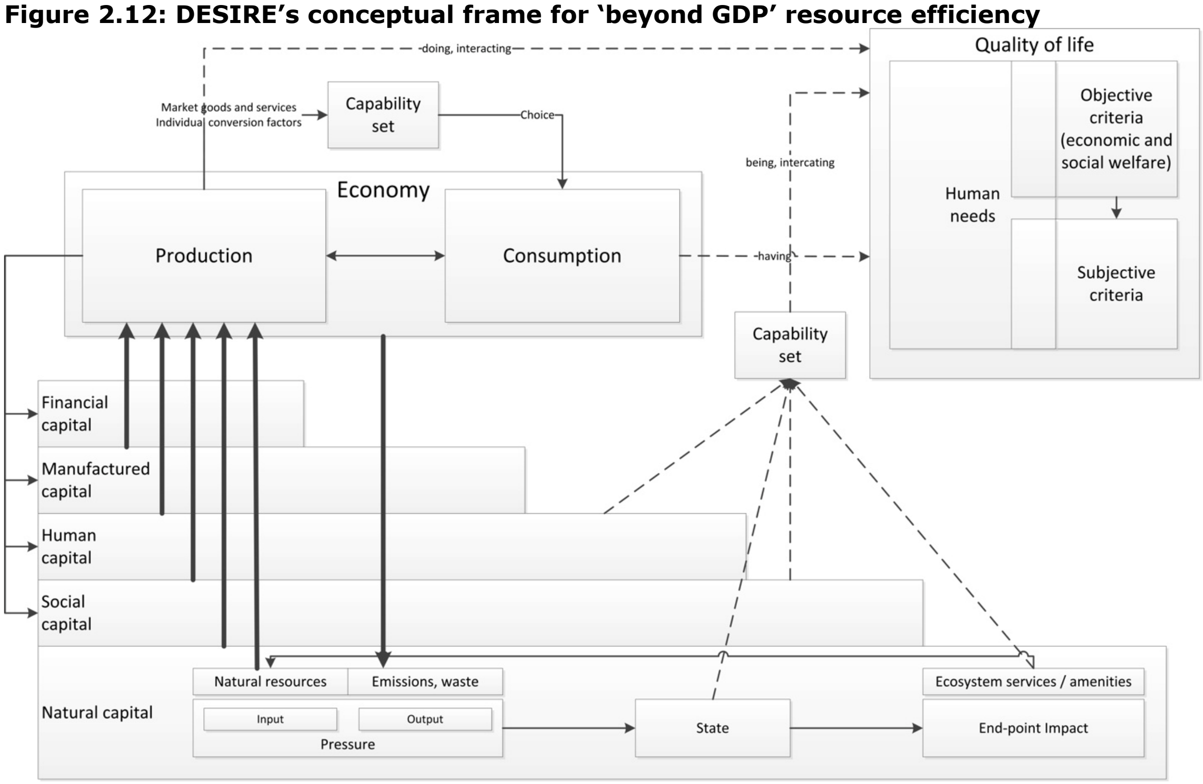
As alternative, Freyling et al. (2014) therefore proposed a preliminary framework where human needs and quality of life are at the core, and it is assessed how the output of economic activities that use natural resources satisfy human needs. This framework was further developed by Usubiaga et al. (2015), of which we provide a brief summary shortly below. The overall objective of this stream of work within DESIRE was to explore whether using alternative reference indicators (i.e. alternatives to GDP or value added) in the calculation of resource productivity or resource efficiency better reflects how the use of natural resources contributes to services to society, i.e. to human needs satisfaction. And accordingly, to conclude whether or not the use of novel reference indicators leads to different conclusions when compared to resource efficiency measures with relation to the economy.

A framework for 'beyond GDP' resource efficiency

The conceptual framework used in DESIRE for the development of 'novel reference indicators' depicts the various mechanisms through which natural capital, social capital, human capital, financial capital and manufactured capital contribute to people's quality of life (or human well-being). This framework integrates elements from Max Neef's human scale development and human needs (Max Neef et al., 1991; Max Neef, 1992), Ekin's four capital model (Ekins, 1992), Sen's capability approach (Sen, 1981, 1985, 1999), as well as the Conference of European Statisticians' recommendations on measuring sustainable development (UNECE, 2014) that builds on previous work of Smits and Hoekstra (2011). In doing so the logic behind the System of National Accounts (SNA) and the System of Environmental-Economic Accounting (SEEA) is followed. Figure 2.12 gives a schematic overview of the conceptual framework.[7]

[7] For a description of all details we refer to chapter 2 and 3 in the report of Usubiaga et al., 2015.

Figure 2.12: DESIRE's conceptual frame for 'beyond GDP' resource efficiency



Source: Usubiaga et al., 2015

Max-Neef considers that human needs are finite, few, classifiable, and non-hierarchal (Max-Neef, 1992). Thus, needs are not dependent on time or cultural factors, they remain invariable. In contrast to needs, their satisfiers are infinite and changeable. Satisfiers go beyond the goods and services provided by the economy. They can take many forms, including that of economic goods. Satisfiers can be seen as the forms of being, having, doing and interacting that represent everything that helps us in a specific time and place to meet our needs. Furthermore, needs remain always constant and inalterable, while the ways individuals choose to satisfy them varies across cultures and time.

Max-Neef grouped human needs in two categories: existential (fulfilling a variety of inherent states of activities) and axiological (value-based), which intercept and form the matrix shown in table 2.2. While the existential category refers to activities such as being, having, doing and interacting, the axiological category covers needs such as subsistence, protection, affection, understanding, participation, idleness, creation, identity and freedom.

Table 2.2: Fundamental Human Needs

Need	Being (qualities)	Having (things)	Doing (actions)	Interacting (settings)
Subsistence	physical and mental health	food, shelter, work	feed, clothe, rest, work	living environment, social setting
Protection	care, adaptability, autonomy	social security, health systems, work	co-operate, plan, take care of, help	social environment, dwelling
Affection	respect, sense of humour, generosity, sensuality	friendships, family, relationships with nature	share, take care of, make love, express emotions	privacy, intimate spaces of togetherness
Understanding	critical capacity, curiosity, intuition	literature, teachers, policies, educational	analyse, study, meditate, investigate,	schools, families, universities, communities,
Participation	receptiveness, dedication, sense of humour	responsibilities, duties, work, rights	cooperate, dissent, express opinions	associations, parties, churches, neighbourhoods
Leisure	imagination, tranquillity, spontaneity	games, parties, peace of mind	day-dream, remember, relax, have fun	landscapes, intimate spaces, places to be alone
Creation	imagination, boldness, inventiveness, curiosity	abilities, skills, work, techniques	invent, build, design, work, compose, interpret	spaces for expression, workshops, audiences
Identity	sense of belonging, self-esteem, consistency	language, religions, work, customs, values, norms	get to know oneself, grow, commit oneself	places one belongs to, everyday settings
Freedom	autonomy, passion, self-esteem, open-mindedness	equal rights, means of communication	dissent, choose, run develop awareness	anywhere

Source: (Max-Neef et al., 1991)

For sector-specific 'alternative' outcome oriented indicators EXIOBASE's MR EE-IO model is not sufficient. In order to connect novel reference indicators to human needs, next to economic indicators on production, income and consumption, functional output and outcome-oriented indicators are needed (most often at the meso or even micro level), as well as subjective indicators. Moreover, an ideal (panel) dataset would than provide explicit information on intentions behind actual consumer expenditures, i.e. to learn which needs are satisfied with certain purchases.

With such a dataset it would be possible to calculate the footprint of the households for every need category according to their expenditure and also calculate the footprint of government consumption in those same categories. In that sense we could assess (1) resource efficiency in terms of objective novel output and outcome indicators and also (2) resource efficiency in terms of subjective well-being.

Cross comparison of such indicators would reveal the (1) efficiency of different regions to provide outcomes from resources, (2) the efficiency of different households to achieve high levels of well-being through resource use, and (3) the different narratives that emerge when comparing indicators based on outcome-oriented and subjective well-being indicators.

Satisfaction of human needs in a resource efficiency context: 3 case studies

We have tried to operationalise this framework by means of three case studies that differ in their scope and level of detail: 1.) linking products in EXIOBASE to human needs (as satisfier), which is, for pragmatic reasons, based on expert judgement rather than the abovementioned 'ideal panel dataset'; 2.) food and nutrition systems (as satisfier for the need *subsistence*); 3.) housing in a resource efficiency context (as satisfier for the need *protection*). The first case study proved that the needs of subsistence and protection are among the most environmentally intensive. This finding formed the rationale to explore their most important satisfiers, food and housing, in more detail in the second an third case study.

2.3.1 Indicator conceptualization and methodology

Case 1: Operationalisation of human needs from an environmental perspective

This case study explored the linkage between consumption of goods and services (and the associated environmental burden) and the needs that these intend to satisfy. EXIOBASE v2.2 is used to calculate the environmental footprints of 200 products and services consumed by households in 43 countries and five 'rest of the world' regions in the year 2007. To bridge the gap between market products and services on the one hand, and human needs on the other, household expenditure has been allocated to the needs each product intends to fulfil.

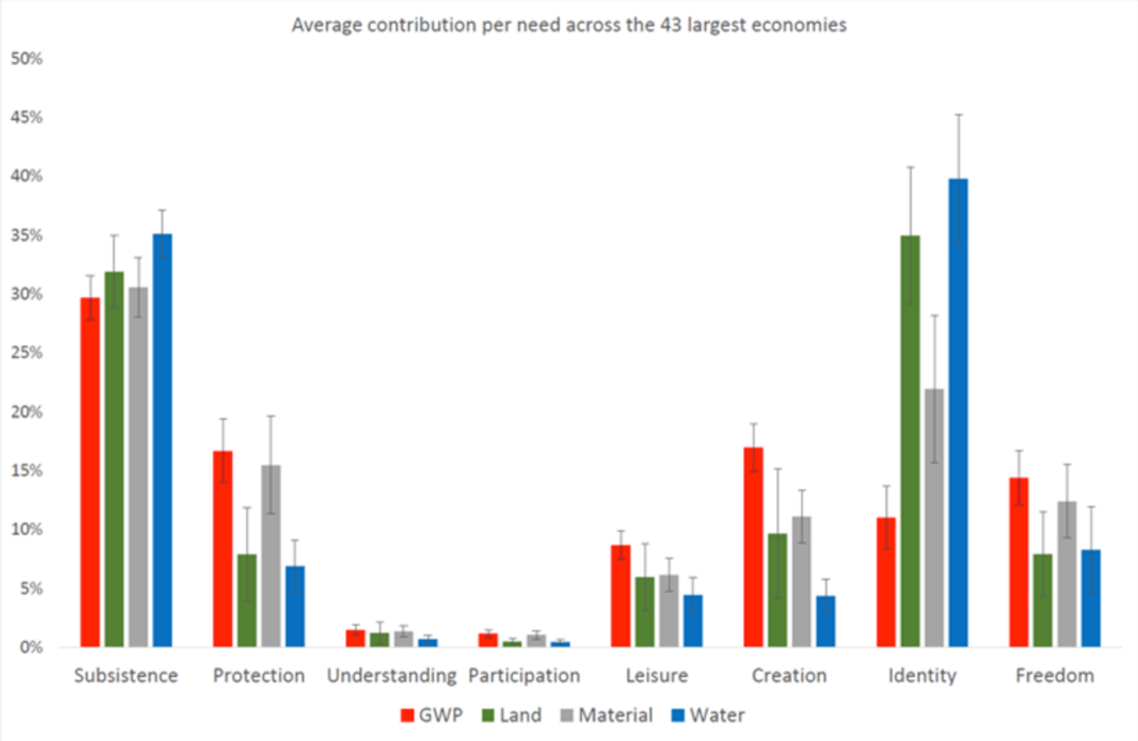
Methodology

To do so, we have first generated a correspondence matrix in which we have connected products to needs. We have tested two different methods to allocate the shares of each product to the corresponding needs. The first method uses a Monte Carlo simulation to randomly distribute the shares. Due to the time required to carry out the simulation, this has only been done for carbon footprint. The second method uses US Consumer Expenditure Survey data for different income groups to undertake the allocation. Thus, we have assumed that the expenditure from the lowest income group in a certain product category attempts to satisfy the most basic need in each case and that expenditure above that threshold in other income groups is meant to satisfy other needs. Due to the lack on the distribution of household expenditure for other countries, we have assumed all the countries to have the same structure as the US in terms of expenditure quintiles. Despite the assumptions, this method is considered more robust to approximate the role of market satisfiers in satisfying human needs. Thus, the results arising from this method have been used to measure the resource efficiency of human need satisfaction, while the Monte Carlo simulation has been taken as reference to check the extent to which the assumptions made affect the allocation process.

Results and discussion

The results obtained from the second allocation method show that subsistence accounts for 30-40% of all footprints for the 43 largest economies. The rest of fundamental human needs do not present such a uniform pattern amongst footprints. Identity takes large part of the land and water footprint whilst subsistence, protection, creation and freedom are the major drivers of the carbon footprint, followed by leisure and identity. Understanding and participation are responsible for a marginal portion of the resource use and emissions amongst nations. None of the market goods in our input-output table seemed to be a satisfier for affection, thus the latter is not reflected in the analysis.

Figure 2.13: Global pressures of human needs satisfaction based on detailed consumer expenditure survey data

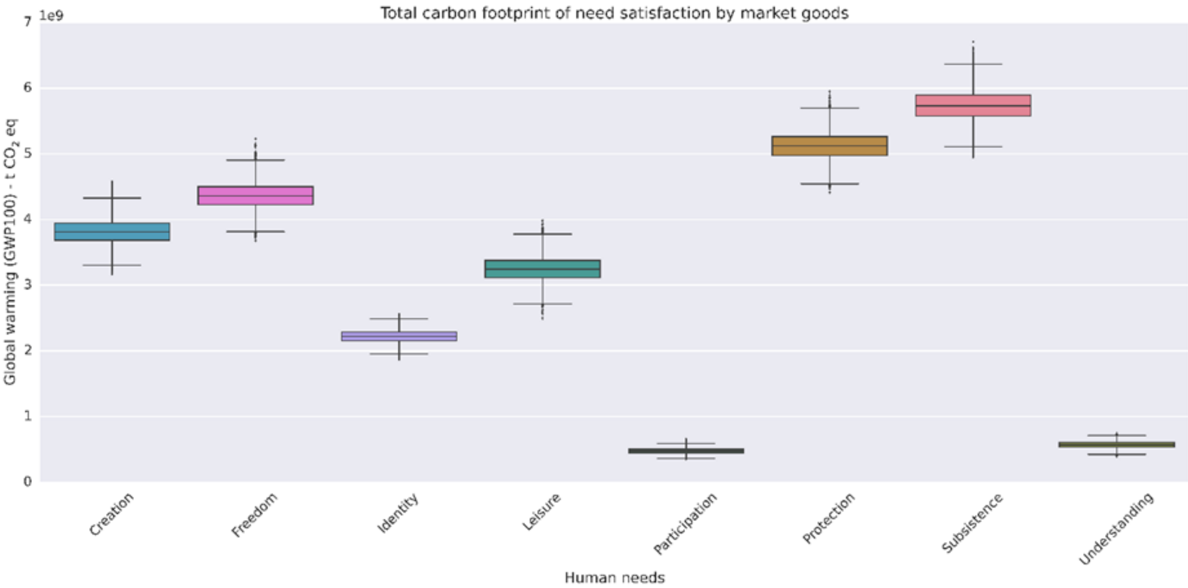


Source: Usubiaga et al., 2015

Compared to the Monte Carlo simulation, we see relatively similar results when it comes to hierarchy of the most environmental intensive human needs. The difference lays in their relative importance.

The results from this exercise show that the different perspectives to assess the satisfaction of subsistence and freedom tend to converge at increased resource use, while those of leisure, understanding, creation and participation only do it moderately. The saturation behaviour of subsistence and freedom is obviously dependent on the indicators used in each case. Hence, future work should also test different satisfaction metrics to check how sensitive our results are to the choice of indicator.

Figure 2.14: Global pressures of human needs satisfaction based on a Monte Carlo simulation

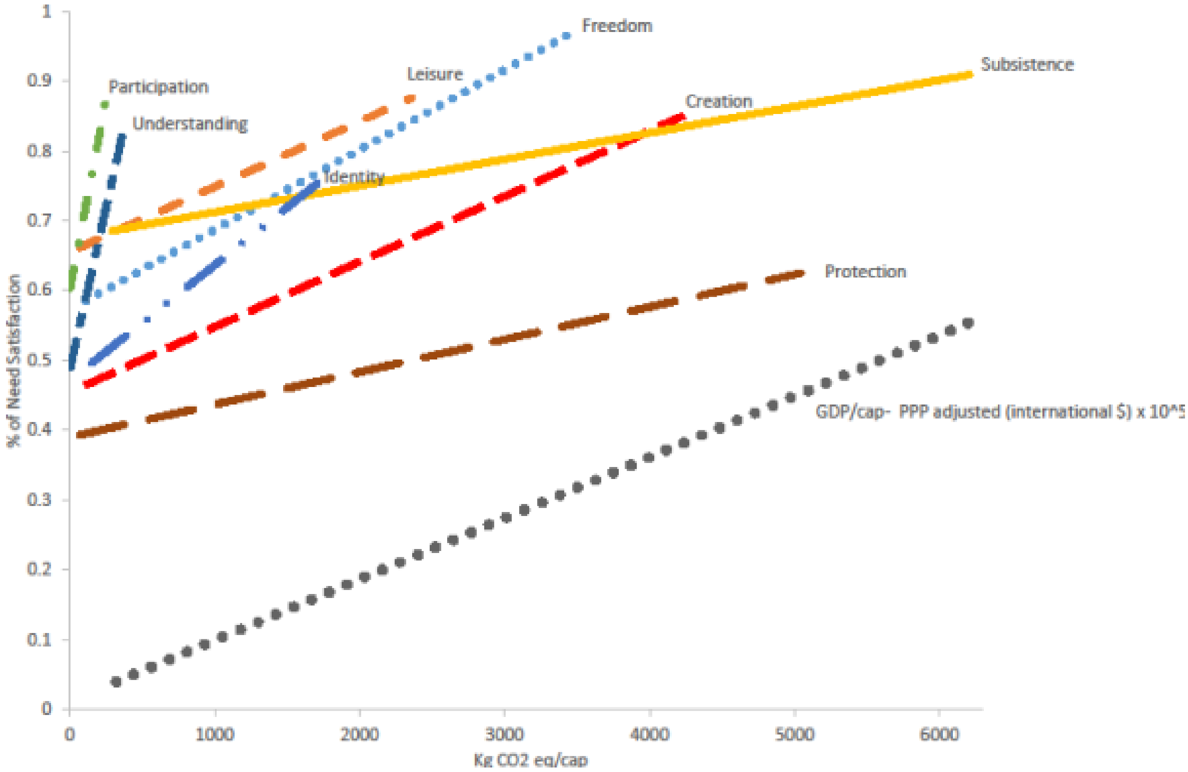


Source: Usubiaga et al., 2015

Figure 2.15 below shows the linear trends between footprints of different needs (on the horizontal axes) and need satisfaction (on the vertical axes). When comparing the resource efficiency values obtained with novel reference indicators to those that use GDP, we see that understanding and participation improve considerably at the expense of low greenhouse gas emissions. In contrast, subsistence and protection lead to much higher emissions without delivering significant gains in the satisfaction of these needs. Nevertheless, GDP has the steepest curve of all indicators. Thus, considering economic wealth as a proxy of prosperity seems to draw an overoptimistic conclusion about the utility of exploiting natural resources when compared to the gains in the satisfaction of other needs.

While interpreting the results, one must keep in mind that the footprint calculation is based on expenditure data, which is related to income and wealth. With this in mind, one can expect that the improvement of need satisfaction in some cases might not be related to environmental pressures, but rather to other socio economic characteristics that drive this.

Figure 2.15: Unweighted average of indicators for need satisfaction (y-axis) in relation to GHG emissions



Source: Usubiaga et al., 2015

Case 2: Human needs and Food in a resource efficiency context

Although food is also linked to other needs such as creation and leisure (e.g. cooking), identity (e.g. food with religious symbolism, eating at expensive restaurants), etc., in this case study it has only been considered in the context of subsistence.

In order to link food to the previously explained conceptual framework, we have reviewed the literature on food and nutrition systems, as well as on food security. We have concluded that the former is the most appropriate one to assess the resource efficiency of food as satisfier of subsistence. The food and nutrition system comprises three subsystems:

- Producer subsystem: Covers the production, processing and distribution of agricultural and food products. The main function of this subsystem is to supply enough food to feed a country's population. Food waste in the production system affects the resource efficiency of the subsystem.
- Consumer subsystem: Households are the main agents. It covers the acquisition, preparation and consumption of food products. The main objective of the subsystem is that individuals consume adequate and varied amounts of food to support health and well-being. Hence, factors such as food waste at consumer level, under/overconsumption, dietary quality and diversity play an important role in assessing whether natural resources are used efficiently.
- Nutrition subsystem: Digestion of food, and transport and utilization of nutrients occur within this subsystem. Insufficient nutritional achievements point out at inefficient use of resources, yet nutritional health depends on many other factors such as a healthy physical environment (including safe drinking water), nutritional

knowledge, sanitation and hygiene, decreased burden of infectious disease, etc. Thus, the relation to resource use is not straightforward.

After carefully considering the existing metrics to characterize each of these subsystems and issues such as data availability, we have selected the following indicators to measure the resource efficiency of the food system.

Table 2.3: Selected reference indicators for each subsystem

Subsystem	Indicator	Unit	Type
Producer	Per capita food available for human consumption	kcal	Output
Consumer	Per capita food intake Per capita net healthy food intake Quality corrected per capita net healthy food intake[8]	kcal kcal kcal	Intermediate output Intermediate output Output
Nutrition	Quality corrected per capita net healthy food intake	kcal	Proxy for outcome

Methodology

The methodology consists of three steps: 1) calculating the material footprint of food consumption, 2) gathering the necessary data and calculating the novel reference indicators, and 3) comparing the resource efficiency of countries using both usual monetary and novel indicators as reference.

The material footprint of countries' food consumption has been estimated by slightly modifying the standard formulation in environmentally extended input-output analysis. In doing so, we have not only considered the final demand of food products, but also the direct consumption of food products embodied in the final consumption of other products and services (e.g. food consumed in hospitals, schools, universities, cinemas, prisons, etc.).

As for the novel reference indicators, food available for human consumption has been calculated after slightly modifying FAO's Food Balance Sheets. For food intake, we have retrieved food waste factors from different sources and estimated the amount of waste that is generated from the moment food is made available for the overall population until it is actually ingested. In the case of net healthy food intake, we have compared per capita food intake figures with average dietary energy requirement data provided by FAO. A value above the latter indicates overconsumption, which is not considered to have a positive contribution to nutritional well-being. Subtracting the calorific content of food ingested in excess from the average dietary energy requirement yields the net healthy food intake. Last, quality corrected net healthy food intake would be estimated by considering quality aspects of the average diet, but it has not been possible to access the necessary data. It should be noted that while the first two indicators can be produced both for individual products and diets, the other two can only be calculated for diets as a whole.

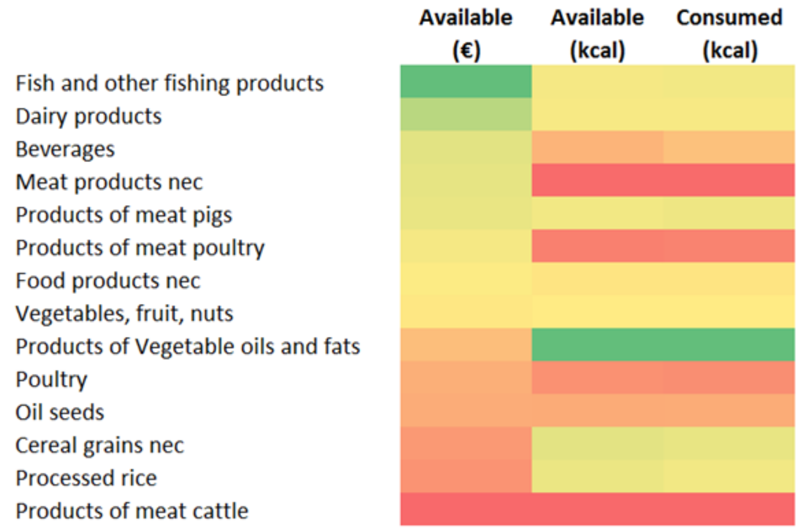
[8] This indicator requires information on country-level dietary quality. Only one source has been found that contained an exhaustive assessment of the quality of food consumption patterns for European countries, yet it has not been possible to access this dataset, so no results are provided for this indicator.

Once the alternative indicators have been calculated, we have compared the material footprint of food consumption (as a whole) with the alternative indicators as well as with expenditure in food. The comparison covers all EU28 Member States in the years 2000, 2005 and 2010. When appropriate, this comparison has also been done at product level.

Results and discussion

A comparison of the resource efficiency of individual product groups in EXIOBASE shows important differences depending on the reference indicator used. When using monetary expenditure, cattle meat, grains products and rice are the most material intensive product categories. In this case, the environmental intensity of some products is hidden by their relative high prices. When considering their caloric content, the price differences between product categories are eliminated thereby leading to more representative values and more pronounced differences between product categories. Thus, using available food or consumed food (represented in kcal), all meat products (including poultry meat and non-specified meat products) arise as the most environmental intensive product groups, while vegetable oils, grain products and rice seem to have a considerably higher material productivity as shown below.

Figure 2.16: Rank-based colour scale of the resource productivity values of the most relevant food products using different indicators as reference



Source: Usubiaga et al., 2015

Comparing countries' performance at diet level, we have also found substantial differences depending on the reference indicator used. As in the case of individual product groups, the removal of the price differences between domestic product groups provides a better measure of how food contributes to well-being, and by extension of its material intensity. Our results suggest that the food consumption patterns of several Eastern countries are more resource efficient than some Western countries if we consider alternative output indicators such as the energetic content of available and consumed food. This is more accentuated when overconsumption is considered.

Figure 2.17: Rank-based colour scale of the resource productivity values of countries using different indicators as reference

Source: Usubiaga et al., 2015

The selection of the most appropriate indicator is not an easy task, since there are trade-offs in terms of RACER criteria (Relevance, Acceptability, Credibility, Easiness, Robustness) between the different metrics. Nevertheless, it can be concluded that monetary indicators do not appropriately reflect the contribution of food to nutritional well-being.

The limitations have to be considered while interpreting the results. With regard to the methodology, the use of per capita figures obscures different food consumption distribution patterns among the population, which results in an overestimation of several indicators at country level. In addition, consistency between the different data sources (e.g. classifications used), and the robustness of waste factors, primary data sources and the draft version of EXIOBASE used (v3.1) should also be highlighted.

Case 3: Human needs and Housing in a resource efficiency context

Housing is one the most important satisfiers of the need of protection, yet there is no consensus around how 'adequate' housing should be defined. In Europe, overcrowding is the problem related to housing that affects most people. This is closely followed by structural problems with the dwelling. Per country, important differences appear between Eastern and some Southern countries, compared to the rest.

From a human needs perspective, the use stage of housing is the most important phase, for a dwelling does not act as a satisfier until it has been fully completed. Following a literature review on the environmental pressures associated with the different life-cycle stages of housing, the construction and maintenance phase has also been considered in the case study due to its high material intensity.

Methodology

For the construction and maintenance phase we have related the associated material footprint to classic monetary and alternative reference indicators. Footprint calculations have been performed using EXIOBASE v3.1. This required certain assumptions to split the activities undertaken within the construction sector between those related to dwellings and those that are not. For the use phase we have related total energy use per purpose – climate-corrected when appropriate – to classic and alternative reference indicators. The necessary data has been obtained from the Odyssee-Mure project (2015) database.

In selecting alternative reference indicators for the construction and use phases, two types of metrics have been considered: Functional output indicators, and deprivation indicators. The latter, which is largely based on data from EU SILC, represents the amount of people who do not fail to satisfy certain 'adequate housing' criteria.

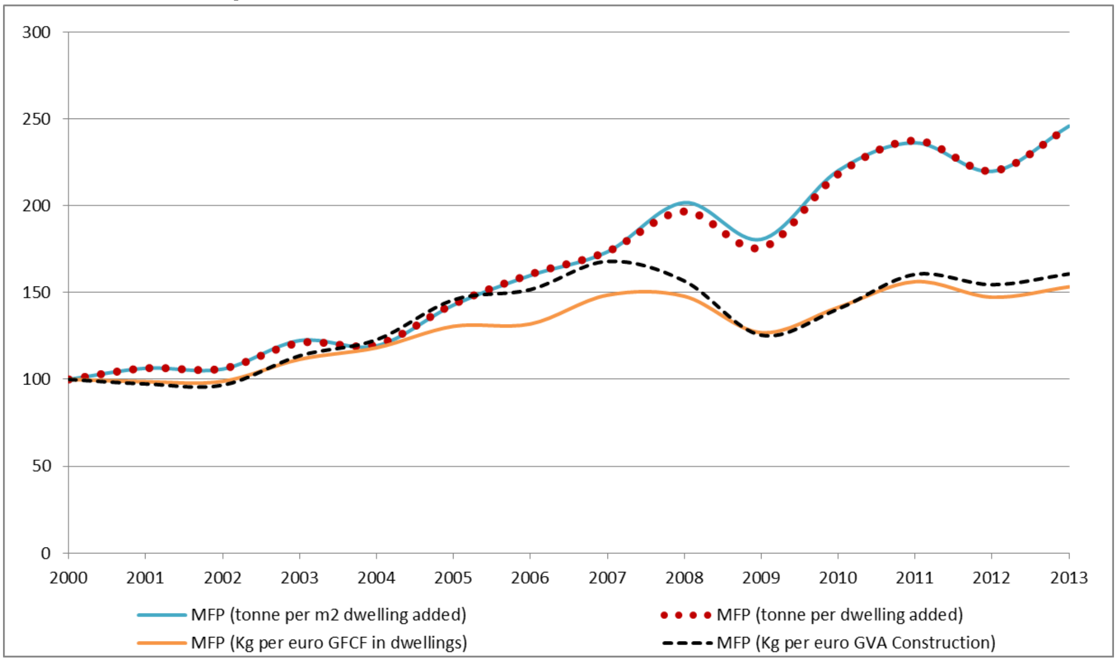
Table 2.4: Selected reference indicators for each life-cycle stage

Phase	Indicator	Unit	Type
Construction and maintenance	Dwellings added to the housing stock	no	Functional output
	Average dwelling floor space added to the housing stock	m^2	Functional output
	People without overcrowding problems	no	Deprivation
	People without structural problems	no	Deprivation
Use	Dwelling	no	Functional output
	Dwelling floor space	m^2	Functional output
	People without problems to keep their homes warm	no	Deprivation

Results and discussion

The analysis of resource efficiency developments in the construction phase of dwellings indicates a generally increasing material intensity of residential construction in Europe. Material inputs to construction work show a clear upward trend in the 2000-2013 period, whereas the actual functional output of dwelling construction declined relatively strong. This implies that the 'functional approach' to measuring resource efficiency in housing show a steadily increasing trend, both in tonnes of material required per dwelling added to the housing stock and tonnes of material per m^2 (in which the trend to larger homes is incorporated).

Figure 2.18 Comparison of Resource Efficiency outcome – 'classic' versus 'functional' for the construction phase



Source: Usubiaga et al., 2015

An increasing trend of material intensity also appears from a 'classic' monetary approach in which the material inputs to construction are put in relation to gross value added of the construction work sector and to gross fixed capital formation in dwellings. Although the pace at which the material intensity of dwelling construction is increasing differs somewhat between the 'functional' and 'classic' approaches, we have no reason to believe that they lead to different conclusions. We do think, however, that a functional approach by relating material inputs to the number of dwellings or m^2 dwelling floor space actually added to the housing stock (or renovated/maintained), is more accurate in some respect. A functional approach is better equipped to capture the trend of increasing dwelling sizes in the EU.

For the use-phase of dwellings we could not identify a clear need for novel or alternative reference indicators. Targeted monitoring of household's resource use by end-use is highly effective to assess developments in resource efficiency. Existing monitoring instruments seem to be spot on.

As for the 'housing deprivation approach' to measuring resource efficiency, the main conclusion is that the EU SILC indicators on housing deprivation are, on its own, effective and easily interpretable indicators. A combination with environmental metrics in a ratio appeared to be somewhat misleading, while decreasing its clarity.

Conclusions on the extent to which indicators of the three "novel reference indicators" case studies could be linked to EXIOBASE

None of the three case studies has managed to completely couple all the proposed alternative reference indicators to the EXIOBASE classification. In specific cases within the food and housing case studies, a one-to-one correspondence between EXIOBASE product groups and the indicators was possible. Nonetheless, besides these exceptions, the indicators proposed should be seen as a separate set of metrics that can only be soft-linked to the input-output model.

The first case study has proposed novel reference indicators at the level of human needs, since there is not simple correspondence between the product groups represented in EXIOBASE and Max-Neef's human needs. Due to the complexity and interlinkages between needs and products, it was not possible to use indicators at product group level that can describe the specific contribution of each product to the need(s) it intends to meet.

In the food case study, indicators at product (food available for human consumption, food intake) and aggregated satisfier level (i.e. food as a whole: food available for human consumption, food intake, net healthy food intake, quality-corrected net healthy food intake) have been proposed.

Strictly speaking the metrics given at product level could be linked to EXIOBASE from the consumption side, but there are two main factors to consider: The first one refers to the correspondence between the primary data source (Food Balance Sheets [FBS]) used to calculate the indicators and EXIOBASE. This correspondence is problematic, since FBS provide information on food made available for human consumption, yet the classification used represents primary products. Before reaching the consumer, most food products are usually processed one way or another, which requires assumptions to link primary products to the manufactured food categories in EXIOBASE.

The robustness of the results depends on these assumptions. Second, food is not only consumed as part of final consumption activities, but also in 'food-related services' such as health services, education, etc. This intermediate consumption is ultimately embodied in the final consumption of other goods and services. In the case study we have not assigned the related food consumption to the end product or service in which it is embodied, but to the food product itself. Hence, the product-level indicators need careful interpretation if they are to be related to individual product groups in EXIOBASE.

With regard to the metrics given for food as an aggregated satisfier, the consumption (intermediate and final) of all food products is combined to depict the per-capita level of nutritional well-being achieved by a country's population. The set of indicators provided at the level of human need are provided separately and could only be soft-linked to the input-output model.

The housing case study has made use of two types of alternative reference indicators: functional output and deprivation. The functional output indicators used as reference for the construction phase (new dwellings built in terms of number and m^2 floor space) can be attributed entirely to the construction sector. However, the activities of the construction sector go beyond building new dwellings (e.g. maintenance work and construction of non-residential infrastructure such as industrial facilities or roads). For this reason, there is not a one-to-one correspondence between the alternative indicator and the product group in EXIOBASE's MRIO model.

As for the use phase, final consumption of energy by households is considered a good reference. In the case study we have used climate-corrected final energy use by purpose (e.g. heating, electrical appliances, etc.) from an external source. In itself indicators on physical amounts of energy use by use purpose are already effective monitoring instruments to assess developments in resource efficiency. There is future research potential to combine these kind of data with the existing EXIOBASE data classification by energy product. In that way footprints of type of energy used can be connected to the use purposes, which would increase the relevance of the functional unit of measurement even more.

The alternative indicators proposed following the deprivation approach relate the functional output indicators to the amount of people who have structural problems or are not able to keep their homes warm. The functional output indicators cover the material footprint or energy consumption of the whole population, while the deprivation indicator refers only to a fraction of the population. Therefore, the latter cannot be linked to the EXIOBASE product groups as an add-on item, but has to be considered separately and interpreted carefully.

2.4 Conclusion on DESIRE's novel indicators: ready for uptake?

In DESIRE's more experimental indicator development, just as in the 'core framework', we tried to causally link pressures stemming from socio-economic and nature interactions to the state of the environment and environmental impacts. In this subsection we generalize the lessons and conclusions from our development of resource efficiency indicators in the three 'novel indicator' domains: critical materials, biodiversity, and novel reference indicators 'beyond GDP'.

Indicator concepts and methodology

A commonality of DESIRE's research efforts in the novel indicator domains is that they required highly detailed information and data, beyond the scope of environmental extensions and the economic IO-framework as included in EXIOBASE. All three novel indicator domains therefore had to follow a case study approach, or in case of biodiversity impacts, had to set a very clear scoping boundary (i.e. bird species loss, mammals extinction risk, carbon sequestration forgone related to a maximum of 16 out of the 163 EXIOBASE production sectors.

Biodiversity is the only novel indicator domain where an appropriate link with DESIRE's EE-IO framework could be made, in particular for 'land use intensive sectors', i.e. agricultural production and forestry. Environmental pressures of production and consumption are, through the link with land use and biomes/species habitats in particular geographical locations, characterized with the EE-IO framework. In addition, only for crop growing and harvesting in the year 2000, explorative calculations were executed on carbon sequestration forgone.

Regarding critical materials the required high level of detail for appropriate substance flow analysis made it a labor intensive as well as methodological challenging task to make sound linkages to EXIOBASE's full EE-IO framework. Rather than full time-series analysis, pragmatically operationalized case studies on EU-level (EU27), for a single year (2007) were performed.

Regarding the research on novel reference indicator 'beyond GDP', just as in the critical materials domain, dedicated case studies needed to be executed to address specificities of resource use and environmental impacts from a human well-being and human needs perspective. None of three novel reference indicator case studies was successful in making a full coupling to the EE-IO framework of EXIOBASE. The primary reason being that there is no one-to-one relation between production and consumption and a broader perspective on welfare and human well-being. EXIOBASE as such is therefore not sufficient for resource efficiency assessments based on other references than GDP or value added.

In line with the findings for critical materials and impact on biodiversity, the general conclusion is that DESIRE's indicator framework could not be complemented with a full set of alternative reference indicators for resource efficiency assessments for all products and sectors included in EXIOBASE. In the next subsection we will elaborate on the results, the involved uncertainty and what this means for indicator uptake.

Results, uncertainties and considerations for indicator uptake

The critical material case studies for Indium, Tantalum and Neodymium resulted in highly detailed flow diagrams of semi-finished products as well as final consumables. The results are especially informative as 'standalone' case study output as each critical material has its own specific use applications and hence impacts of supply risks etc. It is more difficult to draw generalized conclusions on overall resource efficiency. Particularly the Tantalum case study delivered a novel insight (i.e. its importance in hard disks). The Neodymium case, on the other hand, seems to highlight the level of uncertainty involved in the analyses' methodology (a potentially large overestimation of European consumption when compared to absolute numbers from literature sources).

The work on biodiversity impact indicators proofed that the level of detail in which 'land use intensive' economic sectors are covered is crucial to appropriately link economic processes to regional specificities such as species rich biomes and species' habitat preferences. EXIOBASE offers a good framework to track and trace the impacts of production and consumption on biodiversity, however the method depends on availability of good quality spatially explicit auxiliary data on land use changes, biomes and habitats, as well as stocks of vegetation for carbon sequestration. Uncertainties primarily relate to availability and quality of these auxiliary data, in addition to assumptions that had to be made on e.g. the grow back potential of vegetation for carbon sequestration. Especially for the latter, the carbon sequestration results should be considered explorative. For the indicators on bird species loss and extinction risk of mammals, uncertainties arise through averaging impacts on local grid level to country level before 'footprints' can be calculated with EXIOBASE.

Albeit the methodological uncertainties, the first results do provide plausible insights in the causal relation between, for example, agricultural production in, and harvesting of wood from, particular species rich biomes and how this affects other country's 'footprint' of species loss or extinction risk through international trade. Such insights are valuable and can be used immediately in narratives. On the other hand, it might be more difficult for a receiving audience to attach a meaningful interpretation to the indicator results. For example, the average European citizen might not easily understand in what way they can counter any negative impact on e.g. bird species or mammal extinction risks abroad. This probably underscores the need for a good accompanying narrative in relation to the envisaged purpose with the indicator (a topic that we will further address in chapter 4).

Although contextualization of novel reference indicators to calculating resource efficiency is needed, the results of the three different case studies have in common that alternatives to monetary references such as GDP or value added were found to provide relevant, sometimes even more meaningful, insights.

In the food case study we have proposed four indicators (food available for human consumption, food intake, net healthy food intake, quality-corrected net healthy food intake) that describe the role of the different components of the food and nutrition system in meeting the need of subsistence. Compared to monetary indicators each of these metrics has advantages and disadvantages from a RACER perspective. Among the four proposed, only food available for human consumption is provided by a recognised source (FAO). Hence, food available for human consumption has more credibility than the rest, since its methodology is well established. Conversely, this metric does not sufficiently capture the contribution of food to nutritional well-being, since it leaves out key factors such as food waste at consumer level, overconsumption or dietary quality.

For instance, food waste is considered in food intake indicators, overconsumption in net healthy food intake and dietary quality in quality corrected net healthy food intake. Therefore, the relevance of the latter is higher than that of the others (and probably more acceptable in this context), yet it requires making more assumptions that negatively affect its robustness and credibility. The involvement of relevant institutions such as FAO, national statistical offices as well as other relevant stakeholders in methodological and data gathering activities would increase the robustness and credibility of the indicators, and eventually improve acceptance in the policy arena.

As for the work on housing, the alternative indicators selected for the construction phase (number and m^2 of new dwellings) might be more relevant than monetary indicators in criteria such as relevance, which improves its acceptability. This comes at the expense of credibility due to the necessary assumptions to split the footprint, value added and final consumption expenditure of the construction sector between the activities related to dwellings and other construction work. For the use phase, the functional indicator selected (households resource use by purpose, e.g. energy use for space heating) is a clear improvement over monetary metrics. Especially in the field of energy, this type of monitoring is relatively well established and is used to inform energy policies. The latter can rely on other data sources than EXIOBASE, i.e. data from the Odyssee-Mure project.

Our overall conclusion is that it seems to be clear that using alternative indicators as reference yields different results than when using monetary metrics. Given that the latter could potentially be misleading when used in the wrong context, this type of work should be further encouraged to eventually develop better metrics of well-being in general, and resource efficiency in particular. For now, due the level of uncertainty involved, the first results should be used with some caution.

3 Indicator development: optimal set of resource efficiency indicators

After completion of the EE-IO time series, the database could be used for systematic analysis. In this chapter key results are described of: 1.) analyses on driving forces behind resource efficiency indicator results (to help identify the main 'driver' indicators); 2.) calculation methods and possibilities for MR EE-IO model simplification; and 3.) a systematic analysis of options to minimise the indicator set to a small 'optimal' set.

3.1 Driving forces behind Resource Efficiency indicator results

Resource-efficiency indicator results give information on the overall environmental impact, but are not able to capture the driving forces behind resource-efficiency indicator scores. This leaves policy makers with knowledge of how well a socio-economic system is performing, but with little (quantitative) knowledge of why the system is performing as observed. Unravelling the mechanisms that drive performance is considered essential in designing effective policy to attempt to influence future impact.

Drivers of impact can be seen from a number of perspectives – firstly, the temporal aspect where drivers of change in indicators are identified such that impact is analysed over time, and with respect to different socio-economic variables. Secondly, the life-cycle or supply chain perspective, where key actors in the supply chain of a good or service are identified that drive impact. An example here is the understanding of construction requirements used within the provision of services by the services sector. If we shift to a service based society, how dependent do we remain on bricks and mortar? Systematic analysis of indicator results based on the EE-IO model is possible using structural path analysis – where impact pathways are analysed and ranked based on contribution to overall impact. Finally, a combination of the temporal and structural aspects can be integrated into a single analysis by breaking down change into several key parameters of policy interest.

In DESIRE's WP9 (task 9.2), indicators were broken down into the factors population growth, population affluence, changing consumption patterns, changing industrial production, changing trade relationships and changing resource efficiency were explored. For all details of this structural analysis of drivers we refer to Wood et al., 2016.

Globally, environmental impacts are growing. Resource efficiency indicators, however, show different trajectories depending on the perspective taken. Production based resource efficiency indicators (the impact in a certain region) generally show resource efficiency improvements for developed countries, and from a decoupling perspective, we thus see decoupling occurring for production based impacts. From a consumption perspective (the impact embodied in final demand in a certain region, utilising supply-chain analysis) we see a very different picture. Whilst the main regions (EU, US, China) are still generally decoupling, the rate of decoupling is greatly reduced, and turns negative in some cases.

At the country level, especially for wealthy countries and most evident in the EU, we see a much greater rate of negative decoupling (that consumption based impacts are outpacing economic growth). When we look at what is driving this upward growth in resource use, we consistently see the impact of population (small steady upward driver), of affluence (strong usually upward driver), and the impact of trade (moderate upward driver) – both to intermediates and final consumers. In terms of products and supply chains that are driving this growth, we see the effect of the construction activity as being one of the key sectors, particularly across material and greenhouse gas indicators. Downward drivers include both impact intensity (the ratio of impact per unit output) – where we see that this has had a strong downward effect on indicator scores over time; and final demand mix – which has had a weak negative impact on indicator scores over time.

Looking at the drivers of this increased consumption based impacts relative to GDP, we can conclude the following strong trends: 1) there is little evidence of the increased impact being due to changing types of products consumed; 2) construction is the only main exception in terms of product mix – it is also the most relevant activity in terms of a number of environmental impacts and has seen the greatest change over time; 3) trade has shifted strongly from developed to developing countries; 4) the overall impact embodied in trade has greatly increased, in line with the increased volume of, but also due to increased impact per unit of trade – trade has shifted to less efficient producers.

3.2 Optimal calculation methods and level of detail

A fundamental challenge in indicator development by European institutes like EEA and Eurostat is the consumption-based perspective. In this perspective, in essence all impacts along the (global) value chains related to European consumption should be taken into account. This implies that insight is needed in the 'pollution and resources embodied in trade'. Through European Commission regulations it can be ensured that high quality statistical data are available for EU-member states. However, for European institutes, it is much more difficult to ensure that data in the same quality is available for global trade partners. At the same time a full and harmonized (e.g. in terms of international trade and the level of detail) Global Multi-regional Environmentally Extended Input-Output tables with harmonised trade data are needed to assess the 'pollution and resources embodied in trade'.

Yet, from the perspective of official statistics, 'science-based' global MR EE-IO databases such as EXIOBASE version 3 are not preferred for reasons of deviations from original official statistical publications. Trade linking and further detailing of national IO-publications is unavoidable for global environmental impact assessments, however. Within DESIRE's WP9, Tukker et al. (2016) have therefore analysed how national statistical institutes and EU statistical services can be provided with relevant information that may be acceptable to be used. For this purpose the following research activities have been carried out: 1.) a review of methods to calculate pollution embodied in trade; 2.) a review of various global MR EE-IO tables with listing of their pros and cons; and 3.) a review of uncertainties related to calculations based on MR EE-IOs. For the full details of these analyses we refer to the report of Tukker et al. (2016). We only briefly summarise the main findings below.

Calculation methods

Tukker et al. (2016) found that there is a clear need to cover full international value chains to optimally assess footprints, pollution and resource extraction. Global multiregional environmentally extended input-output databases seem to be the best source to base calculations on as they not only cover full value chains but also are consistent between the production and consumption perspective. The latter meaning that total emissions and resource extraction by all economic sectors in all countries equal the footprint of global final demand. In contrast, the often used Domestic Technology Assumption (DTA), where it is assumed that imports are made in the same way as domestic production, can lead to erroneous results since production technologies and hence associated environmental impacts can actually vary quite significantly across countries. This is especially apparent in imports of small countries, which often have a fundamentally different production structure than the import's country of origin. The DTA (including the slightly better price adjusted DTA) can therefore best be used as a 'last resort calculation method'.

Deeper analyses of calculations based on global MR EE-IO databases showed that differences in allocation principles, definitions and data sources for extensions matter for the footprint results and associated level of uncertainty. The former relates to using a residential instead of a territorial approach. The residential approach takes a global consumption perspective and herewith accounts for all activities/emissions and resource uses in individual countries along the global value chain (including e.g. fuel bunkers). The analyses proofed that different allocation mechanism cause fundamental differences in footprint outcomes. The analysis further showed that differences environmental extension datasets (on e.g. national industrial emission totals) is a cause of uncertainty and differences in calculated country footprints. We will elaborate on this below.

Level of detail

Regarding the level of detail of global MR EE-IO tables, Tukker et al. (2016) concluded that for economic analysis purposes an aggregated sector structure (such as the 30 sectors in the OECD/WTO's Trade in Value Added database) is quite appropriate. For the calculation and analyses of carbon footprints, aggregated EE-IO tables with sector detail of 30-60 sectors (such as the WIOD or GRAM databases), still provide plausible results.

However, for the calculation of water, material and land footprints, a high level of sector/product detail proved to be essential. Aggregating EXIOBASE to the standard 60 products or sectors that Eurostat uses in official SUT and IO publications, led to clear changes in country footprints. When one wants to look at the environmental footprint of specific product groups, detail certainly is essential. The reason behind is that the material intensity, water intensity and land intensity of specific product categories/industry sectors varies much more than e.g. the carbon intensity or the created value added.

Moreover, the level of detail of environmental and material extensions like CO_2 emissions, other emissions, resource extractions, water use and land use is perhaps even the single biggest cause of differences in calculated country footprints. Harmonization of extensions across the various global MR EE-IO databases seems to be a relatively easy option to significantly reduce uncertainty of footprint results (e.g. by using the resource extraction database as recently developed by the UN International Resources Panel). Although further work is still needed here on water, land and emission extensions, it is likely that using a harmonized source for extensions will reduce the level of uncertainty in footprint calculations with more than 50%.

Possibilities to simplify EE-IO data?

The overall conclusion of Tukker et al. (2016) is that for land, water and material footprint calculations no simplification of global MR EE-IOs in terms of a low sector resolution is possible. It is likely that detailed databases such as EXIOBASE will provide superior results over less detailed databases. For carbon footprints and particularly value added, this highly detailed sector resolution is less relevant.

3.3 "Optimal" Indicators

As final task in DESIRE's work package 9 the potential for reducing the number of indicators for environmental assessments is examined through application of a statistical Principal Component Analysis (PCA) in combination with multiple linear regression. This methodology has been applied by Steinmann and Huijbregts (2016) to two fundamentally different datasets, both with the objective to identify a [statistical] optimal (i.e. smallest) indicator set. The rationale behind is that it might be unpractical to base decisions on product Life Cycle Analysis (LCA) or on environmental policy on a large number of indicators simultaneously. The objective therefore was to identify a limited set of indicators that is sufficiently small for efficient decision making and at the same time still covers overall environmental impact, i.e. covering both midpoint impacts of resource use and the full cause-and effect chain in damage-based or endpoint environmental impacts (e.g. impacts on ecosystems and/or human health).

To find an optimal set of environmental indicators to cover the variance in the rankings of a large number of products, the PCA is first based on a selection of 976 products and 135 environmental indicators from the Ecoinvent 3.1 database (Moreno Ruiz et al., 2013) and, secondly, on 93 impact indicators for 7589 product-sector combinations from the EXIOBASE database. The PCA has been combined with multiple regression analysis to arrive at a minimum set of indicators explaining the variance in the product ranking. In addition the extent to which four commonly used resource-based indicators (fossil energy, water, land and materials) are representative of the total variation in product rankings is tested.

Whether based on the life cycle impacts per kg of material or the impacts per million euros of consumption, strong correlations between the different indicators of impact were found. This means that there is a large potential for reducing the number of indicators.
The analysis based on the Ecoinvent database showed that 92% of the variance in product rankings is covered by only 4 out of the 135 initial environmental indicators. A set of six indicators covered slightly more of the statistical variance (i.e. 92,3%). This best set of six indicators relates to climate change, ozone depletion, terrestrial ecotoxicity, the combined ecosystem effects of acidification & eutrophication, marine ecotoxicity and land use.

In addition, the four resource-based indicators together accounted for 82% of the variance in material rankings. The results suggest that it is best to use the fossil energy indicator if just one of the simple resource-based indicators has to be selected. With an explained variance of 72.9% this seems to be a reasonably good indicator of overall impact. The explained variance can be raised to 76.8% by adding material use. Adding land use raised the explained variance to 80.1%, while a set of all four resource-based indicators, including water use, covers 82.0% of the total variance in our dataset. The water footprint appeared to be less important than the other footprints for our dataset;

this is due to the fact that water consumption is related to both the energy-intensive process of electricity generation and the land-intensive process of crop production.

For the EXIOBASE dataset the 93 environmental impact indicators could be reduced to seven indicators related to freshwater and marine ecotoxicity, photochemical oxidation, climate change, acidification & eutrophication, photochemical ozone formation and blue water withdrawal. These seven indicators together covered more than 90% of the variation. Similar to the analysis on the Ecoinvent dataset, the performance of the resource based indicators was also tested. The four resource-based footprints together accounted for only 49% of the variance in product-sector rankings. This means that sets of 1 to 4 resource indicators cannot cover the same amount of variance that can be explained by one toxicity indicator. Supplementing, however, the two best resource-based indicators (energy and land) with the best toxicity indicator (freshwater aquatic ecotoxicity potential, infinite time horizon) the explained variance is increased to 74.8%.

While the optimal sets maximize the amount of covered variance, the recommended indicators are not necessarily the most preferable using additional criteria, such as the RACER (Relevant, Accepted, Credible, Easy and Robust) criteria. For both datasets there are several indicators with approximately the same amount of explanatory power. This means that alternative sets of indicators can be defined which are only marginally worse in terms of explained variance compared to the statistically preferred set of four and seven indicators proposed here.

In both cases, only three out of the four resource-based indicators seem to be of real added value. For both datasets these were the indicators of energy, land and material. This is due to the fact that the (agricultural) water consumption is strongly correlated to the land footprint, especially in the EXIOBASE dataset, making one of the two indicators redundant. Using two or three simple resource based indicators would eliminate the need for the complicated mid- and endpoint damage models, but has limited coverage of the impacts associated with toxic emissions, especially for the EXIOBASE dataset.

The overall conclusion based on the statistical analyses to test options to reduce the environmental indicator set is that the large set of indicators can indeed be reduced to a small key set, representing the major part of the variation in environmental life cycle impacts between materials and of the variation in product-sector combination in a Multiregional Input-Output model.

4 Towards indicator implementation

Now we have summarized the key results of DESIRE's different work packages and converted these into conclusions, we devote this last chapter on a roadmap towards indicator implementation and options for institutionalization of indicators based on global Environmentally Extended Input-Output databases such as EXIOBASE. In doing so we elaborate on a discussion note that functioned as input to stakeholder discussions during the project's final conference. Recommendations we took home from this last 'brokerage and dissemination event' are integrated in the indicator implementation roadmap.

A major accomplishment of the DESIRE project is to add a time series perspective to EXIOBASE. With the EE-MRIO dataset of EXIOBASE version 3, a powerful tool is now available for analysis of various environmental-economic relations in Europe and beyond. Databases like EXIOBASE e.g. help to provide insights about how consumption drives environmental pressures. EXIOBASE thus is a relevant information source in support of evidence based policy related to e.g. Resource Efficiency and the Circular Economy.

So far, however, the development of the database and first analyses based on it, has been primarily a scientific undertaking. The challenge now is to bridge the gap between this scientific research initiative towards uptake and implementation of indicators in policy processes. One thing that we have learned during various policy-science brokerage and dissemination events is that a more formal status of Environmentally Extended Multiregional Input-Output models is for some users an important precondition for indicator uptake. From this perspective, it is desirable when supra-national statistical institutions adopt databases such as EXIOBASE and further develop these along the lines of international harmonized standards.

On the other hand we have learned that even without such formal institutionalization, and sometimes even with indicators that still have room for methodological or data quality improvement, information from databases as EXIOBASE can already be relevant as 'early signalling' or 'agenda setting' mechanism.

In this chapter we will place the 'core set' of the DESIRE indicator framework, as well as the more novel indicator results, in the context of discussions throughout the project on indicator uptake and implementation. With this we aim to develop an indicator implementation roadmap in which we qualify indicators that already have a "statistical stamp" and could be taken-up in policy processes without further needs for improvement, as well as defining next steps to further improve indicators that are relevant but currently lack the full "statistical quality stamp".

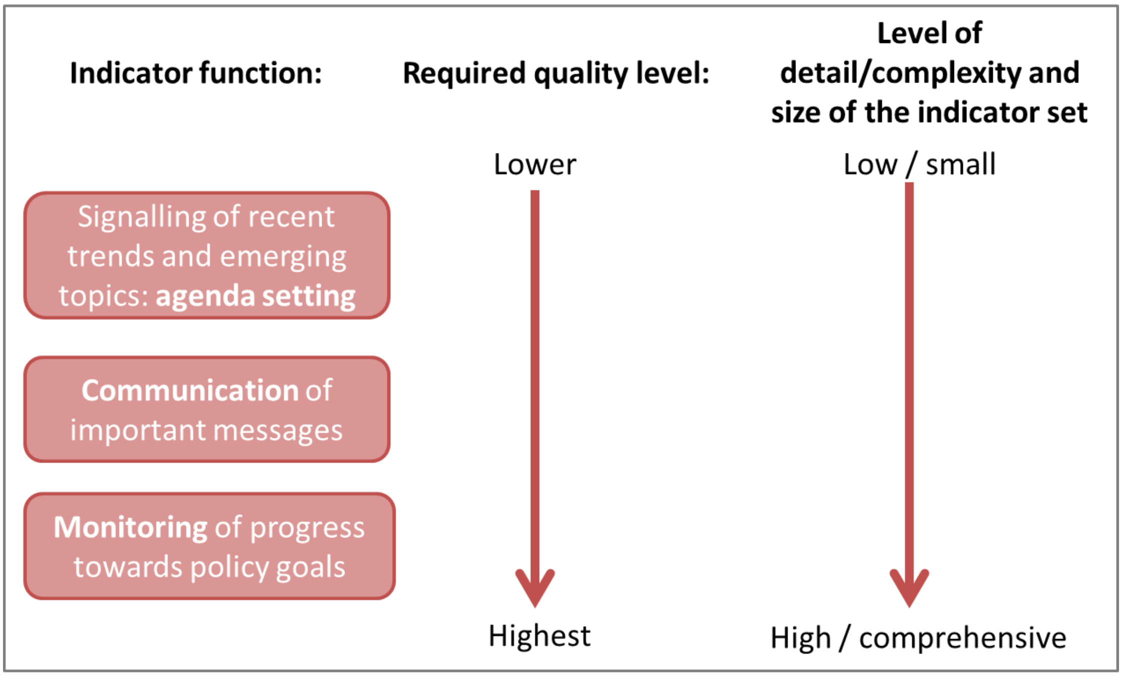
4.1 Uptake and institutionalisation of DESIRE indicators

DESIRE's global environmentally extended input-output time series database, EXIOBASE version 3, primarily offers a rich knowledge base on which a large set of indicators can be calculated, customized to different analytical purposes or policy needs. In a discussion on potential users of EXIOBASE during DESIRE's final conference on the 21st of January 2016 in Brussels, it was for example stated that DG JRC could definitely use the indicator framework with underlying raw data for policy-support research. Other (potential) users might have other information needs for other purposes, for which the required data and indicator quality also might differ. It is for this reason that we will report in this section how DESIRE's indicator framework, in its current state of development and quality level, can be used for different purposes.

4.1.1 Indicator functions: different use purposes, different needs

What should the indicators do?

Figure 4.1: Indicator function and the required level of quality and detail



1. Signalling and agenda setting: plausible information on recent trends.

One of the lessons we took home from the final conference is that indicators may not have to be of perfect quality yet to signal relevant environmental-economic trends. There is a trade-off between precision and the relevance to inform ongoing policy processes. It was stated that feeding policy processes with relevant (new) information sometimes is more important than waiting for the moment when indicators are of perfect methodological and statistical quality. The latter can be taken up further during formal institutionalization processes.

During the conference a general need for timeliness of indicator results (i.e. showing recent developments based on up-to-date data) was expressed, however it is acknowledged that there often is a time lag in official statistics. In this context the now-casted data of EXIOBASE can already play a role, although there are uncertainties given that GDP is used as primary indicator for the nowcasting (for reasons of high correlation) in combination with trends from earlier data points.

We acknowledge that this methodology works better for environmental indicators related to energy and carbon and has a higher level of uncertainty for material indicators. The latter category would clearly benefit from timely available official statistics. The now-casted data are not yet usable for formal monitoring and in cases where accountability is at stake. However, to communicate trends with the idea to trigger debate on the need and possibilities to intervene with policy action, EXIOBASE's now-casted data can be a useful information source already.

2. Communication

Early signals and trends can be communicated to policy departments, politicians and the general public, with the aim to stress a sense of urgency and to trigger debate. Easy to understand, yet credible messages are relevant for this indicator purpose. A smaller set of indicators probably enhances the easiness to digest the communicated messages. In this context, DESIRE's indicator optimization results can come in helpful, especially as there appears to exist strong correlation between various environmental impact indicators. For the purpose of triggering debate there is no use to communicate results of different indicators that are strongly correlated. However, it is recommended to carefully select the indicators with (potentially) higher scores on RACER-criteria *easiness* and *acceptance.* We underscore ones more that the toxicity indicators that came out of the statistical optimization analysis might than not be the best choice per se. Careful selection of indicators to support the message one would like to communicate will enhance the meaningfulness of information for the targeted audience.

During a discussion at the DESIRE final conference it was stressed that choices for specific indicators to communicate, might potentially "hide" misleading messages. For example, a too strong focus on resource inputs and waste outputs (e.g. in the context of a Circular Economy) might have a risk of losing focus on carbon dioxide emissions (e.g. in the context of Climate Action). Whereas perhaps the largest "waste" of socio-economic and nature interactions are related to energy and associated carbon emissions. In the same vain it was mentioned that outcomes of Raw Material Consumption calculations might be dominated by the relatively high mass volumes of gravel and sand.

In this context it was recognized as an asset of EXIOBASE that many economic-environmental relations can be shown and communicated. There is value in communicating cause and effect chains of economic-environmental interaction to a wider audience. Probably credibility is more important here than precision to the last decimal. EXIOBASE seems to be fit for this purpose already.

3. Monitoring of progress towards policy goals and targets

A third function of resource efficiency and environmental impact indicators stemming from EXIOBASE relates more to the end of the policy cycle, where progress towards formal goals and targets is monitored. This is where formal institutionalization, stricter requirements for data quality and comprehensiveness will come into play. This is the reason why this indicator function is situated in the lower part of figure 4.1.

How do DESIRE's 'core indicators' and 'novel indicators' currently fit to these purposes?

We consider the 'core data set' of EXIOBASE, i.e. the **historical data** for the years **1995-2011,** covering *resource use, resource efficiency* and *environmental impact* (i.e. the resource inputs and (metabolic) outputs of *energy, materials, waste, land* and *emissions*) in relation to society-nature interactions through production and consumption (including international trade), ready for immediate uptake, fitting all three abovementioned use purposes.

We do need to stress, however, that there are deviations from official (national) statistical publications. Due the high level of detail imposed, and the need for balancing international trade, deviations from official statistical sources are unavoidable (we will elaborate on this in section 4.2). Moreover, the time series are created with the idea to arrive at plausible year-to-year changes. In the construction of time series, as many official data sources with highest level of detail as possible, are used to respect structural changes in national economies. However, balancing the system (i.e. meeting restrictive conditions such as assuring that total supply matches total use) unavoidably implied deviations from official (National Accounts) statistics. For these reasons, one can expect to find deviations from other historical statistical sources when comparing actual numbers from EXIOBASE. It is for this reason that EXIOBASE indicators, in general, do not have a "statistical stamp". The year-to-year trends are considered plausible, however.

As already mentioned in the previous subsection, the now-casted data (i.e. the **years 2012-2016**), have a higher level of uncertainty because of estimations based on earlier data points and (partially assumed) correlations. For this reason these now-casted years better serve signaling and agenda setting purposes.

Particularly in relation to monitoring progress in the 5 priority areas of the Circular Economy Package, it was asked during the final conference how DESIRE indicators fit. As for the priority areas *plastics*, *food waste*, and *construction and demolition*, EXIOBASE offers relevant as well as plausible information. During the discussion it was said that EXIOBASE can only to a lesser extend provide information on the priority area *biomass and biobased products*. Related to the priority area of *critical materials*, DESIRE's 'novel indicator' development efforts only delivered insight in production and consumption flows for a small selection of case studies, covering a single year. The results are informative, yet not sufficient to fully support monitoring purposes in the this priority area field of the Circular Economy Package.

The results of the other 'novel indicator domains', biodiversity and novel reference indicators (beyond GDP), are subject to methodological challenges and uncertainties related to, sometimes strong, assumptions made. Albeit these methodological challenges that indicate a need for further development, the first explorative results do provide relevant insights in the different cases.

In the case of biodiversity, the results on bird species loss, mammal extinction risk and forgone carbon sequestration clearly point to environmental impacts related to production, trade and consumption of specific sectors and products. These insights can surely be used for communication purposes. It is then recommended to accompany the indicator results with a clear narrative in order to enhance the meaningfulness for the targeted audience. Narratives are equally important when using novel reference indicators 'beyond GDP'. We have found that other indicators than GDP or value added can be relevant and meaningful, however that good contextualization to calculating resource efficiency is needed. Due to methodological challenges and assumption made, in addition to the fact that subjective views can easily be at stake, signalling and communication with the aim to trigger debate must, for now, probably be the dominant use purposes. In specific fields, auxiliary data sources to EXIOBASE (e.g. EU-SILC and Odyssee-Mure) offer relevant information for monitoring purposes. In some cases these data can be better used as such, complementary to EXIOBASE rather than integrated.

4.1.2 Indicator institutionalization

From the perspective of Eurostat, which, besides provision of official statistics, has harmonization of statistical methodology as task, institutionalization of DESIRE's results is an important condition for implementation. Regular updates of EXIOBASE are required for formal institutionalization.

The normal procedure of Eurostat is to formally ask EU member States to submit data in a predefined (hence harmonized) format. Formal data collection with regard to EXIOBASE can thus only be the final step in an institutionalization procedure. This means that attention should first go to harmonization of data and indicator concepts and methods. In this context it was mentioned during final conference discussions that a comparison of methodology, level of detail, etc. with other existing global multiregional EE-IO databases would be highly relevant. Results of such a comparison could then feed into Eurostat's deliberations on the best statistical methodology and the way forward (e.g. in relation with ongoing processes with regard to the Trade in Value Added database, together with the OECD and WTO).

Within DESIRE's WP9, a brief comparative analysis with other existing global MR EE-IO databases, all with their own specific strengths and weaknesses, has been carried out. The main characteristics of the currently available global MR IO databases are shown in table 4.1. The main conclusions of the comparison are that:

- the high level of product/sector detail of EXIOBASE is in particular important for agricultural-, industrial-/manufacturing- (e.g. metal) and energy-producing sectors in relation to environmental issues associated with land use, water use, or resource use.
- IDE-JETRO's AIIOTs, in contrast, offers the longest time series (with a data point back to 1975), with a relatively detailed product classification (76 sectors). A weakness, however, is its small country coverage. On the other hand, the manual handling of data transformation enables a high level of harmonization among constituent national tables.
- EORA and GTAP discern considerably more countries than WIOD, EXIOBASE, IDE's AIIOT or GRAM. This has important advantages in assessing impacts of final consumption that take place in relatively poor countries with a low GDP not covered in other databases (Lenzen et al., 2012). Moreover, a large separate country coverage (as opposed to a large aggregated RoW regions) is important to attribute impacts to individual countries.
- Overall, with its broad coverage of countries and varying sector detail per country, EORA seems to split up the global economy in most products and sectors and it is the only database that provides uncertainty information for its estimates.
- WIOD, to conclude, has some clear advantages with regard to institutionalization as it is the only database with a consistent annual time series in both current and previous year's prices, as well as it is fully consistent with the National Accounts statistics which is important when a link is required to other (socio-)economic data (e.g. for productivity analyses).

Related to institutionalization of DESIRE's results it was stated during the final conference discussions that there recently seemed to be more emphasis on expanding the level of detail in NACE financial- and other service sectors in data collection for official statistics. The comparison between EXIOBASE and other existing global MR EE-IO databases, as well as other analyses within DESIRE's WP9 on the optimal level of detail, made clear that a high sector- and product detail is crucial for meaningful assessments of environment-economic interactions and resource efficiency. In the same context it was underscored that policy demand drives the development of official statistics and the associated level of detail that indicators can provide. There is thus a need for coordination between European Member State's and the European Commission's policy departments and statistical institutes in the formal institutionalization process of MR EE-IO databases as EXIOBASE to ensure a minimum required level of detail in sectors/products with high environmental-economic interactions.

Table 4.1: Review of the main Global Multiregional Input-Output databases

Database name	Countries	Type	Detail (ixp)*	Time	Extensions	Approach
EORA	World (around 150)	MR SUT/ IOT	Variable (20-500)	1990-2012	Various	Create initial estimate; gather all data in original formats; formulate constraints; detect and judge inconsistencies; let routine calculate global MR SUT/IOT
EXIOBASE	World (43+RoW)	MR SUT	163-200	1995-2012	30 emissions, 60 IEA energy carriers, water, land, 80 resources	Use COMTRADE/BACI in combination with imports and exports from SUT to create a harmonized trade database, impose trade on national SUT, detail and harmonize national SUT; use global statistics and national SUT as constraints to create time series
WIOD	World (40+RoW)	MR SUT	35x59	1995-2011, annually	Detailed socio-economic and environmental satellite accounts	Harmonize SUTs; create bilateral trade database for goods and services; adopt import shares to split use into domestic and imported use; trade information for RoW is used to reconcile bilateral trade shares; add extensions
GTAP-MRIO	World (129)	MR IOT	57x57	1990, 1992, 1995, 1997, 2001, 2004, 2007	5 (GWP), Land use (18 AEZ), energy volumes, migration	Harmonize trade; use IOTs to link trade sets; IOT balanced with trade and macro-economic data
GRAM	World (40)	MR IOT	48x48	2000, 2004	Various	Use harmonized OECD IOTs; neglect differences like ixi and pxp; use OECD bilateral trade database to trade link.
IDE-JETRO	Asia-Pacific (8: 1975) (10: 1985-2005)	MR IOT	56x56 (1975) 78x78 (1985-1995), 76x76 (2000, 2005)	1975-2005	Employment matrices (2000, 2005)	Harmonize IOTs based on cross-country survey information; link via trade, manual balancing to reduce discrepancies within certain bounds.
OECD Trade in Value Added / ICOA	World (61 – EU28, G20, other major economies)	MR IOT	34	1995, 2000, 2005 and 2008 to 2011	Value added. Carbon, materials investigated	Based on OECD’s harmonized bilateral trade databases and IOTs

* i = number of industries, p = number of products, **
Source: Tukker et al., 2016

4.2 Recommendations on creating footprint data with a "statistical stamp", actions and timeline

In chapter 3 we concluded that global MR EE-IO models are the preferred calculation method for consumption based accounting of footprints, for which a high level of product sector detail is required to obtain relevant results. At the same time it should be acknowledged that the compilation of global multi-regional input-output databases requires a high level of harmonization and consolidation of often conflicting data sources. For this reason, there is no other option than to deviate (sometimes significantly) from official statistics that national statistical institutes provide. One key reason is that all imports, summed to a global total, do not match the global total of exports, whereas in reality international trade obviously is a zero-sum game. The same imbalances between imports and exports occur when bilateral origin-destination trade flows are confronted with each other. Given that national statistical institutes have a national mandate, it is one of the main reasons that the construction of global (EE) MR-IO databases such as EXIOBASE has mostly been efforts of scientific research consortia. An important question for formal institutionalization is thus how a "statistical stamp" can be attributed to databases as EXIOBASE and the calculation of environmental footprints.

The first and fundamental solution to the main problem of imbalances in international trade data, and perhaps the "Royal route", is that all national statistical institutes (NSIs) in the World collaborate, e.g. within the context of the UN Commission on Economic and Environmental Accounts (UN CEEA), on a data exchange platform that allows NSIs to end-up with supply and use tables as well as input-output tables that are mutually consistent between countries. This, however, is likely to be a **long-term** endeavor, unlikely to provide results in the coming 5 years. Our recommendation for this longer term solution is that NSIs and supra-national statistical institutions make use of the experiences from global (EE) MR-IO practitioners to identify the most pressing data inconsistencies at international level.

Based on suggestions of Edens et al. (2015) a second approach is described by Tukker et al. (2016): using a "Single-country National Accounts Consistent" footprint approach. In this approach, an existing global MR-IO database will be adjusted for the single country of investigation, by using the IO-data and environmental extensions from official national statistical sources and fixing these (i.e. imposing a restrictive condition that these national totals cannot change) before rebalancing the whole global MR-IO database again. Only after this rebalancing, the footprints for the country of interest can be calculated in a way that is aligned with national accounts and other official statistics.

The main drawback of this method is, however, that plugging-in the national data in the global MR-IO database and rebalancing the model is labor intensive. Moreover, uncertainties may increase for cross-country footprint comparisons, e.g. as different extension data sources are now confronted with each other (see earlier remarks of this being a potentially big cause of uncertainty).

There currently is one global multiregional input-output database that is produced by a supra-national organization, i.e. the OECD/WTO Trade in Value Added database (TiVA). A further, and more preferred, refinement of a footprint calculation approach with a "statistical stamp" can thus be to use this TiVA database as a starting point. This is a trade-balanced database but with a coverage of 30 sectors too aggregated for the calculation of water- material-, land- and emission footprints. A way forward is to use the detailing procedures as developed particularly for EXIOBASE, and the optimization procedures as developed for EORA, to arrive at a level of 100-200 industry sectors that is appropriate to perform proper footprint calculations. Lastly it is recommended to use internationally harmonized data sets for carbon emissions (e.g. based on IPCCC or IEA energy flows plus emission factors), materials (e.g. the recently published UNEP International Resources Panel), land and water, and add these to the more detailed TiVA database.

In this way, a database could be created that at an aggregated level has the "statistical stamp" provided by the OECD, uses extensions that are harmonized/commonly accepted, but also can provide more detailed information (through a procedure backed by a number of credible, scientific institutes). This would, for the first time, give a global multiregional input-output database that probably has a higher level of credibility as the individual scientific databases such as WIOD, EXIOBASE, GTAP or EORA. Such a database, that holds a middle ground between official statistics and scientific work, could be a good compromise for any NSI or practitioner to work with.

Our recommendations for the **short term,** in addition to moving forward based on the TiVA database as just described, are to agree in the formal statistical gremia on:

- a preferred and harmonized way to calculate footprints (i.e. using a true global value chain approach rather than other allocation mechanisms;
- in doing so, taking the residential perspective as starting point;
- and avoiding neglecting emissions or resource uses related to e.g. international bunkers;
- ensure the use of harmonized extensions databases.

It is likely that such an approach will significantly reduce differences in footprint calculations for countries. Moreover, given the importance for environmental-economic interactions on a global level, in which Europe is an important driver for environmental impacts outside the EU, it is recommended that the EU uses such a harmonized data and analysis tool in a role of "knowledge broker" to non-EU countries on how objectives such as the UN Sustainable Development Goals can be met.

Concluding actions of the DESIRE consortium

- The DESIRE projected formally ended the End of February 2016 such that the consortium has nu funds to maintain and update the database significantly.
- In due time, EXIOBASE version 3 will be made available (with access upon request) through EXIOBASE's website.
- In addition, in the course of time, (graphical) case study results will as much as possible be published on the website.

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Annex 1: Initial evaluation of Resource Efficiency Indicators

Results of the RACER-evaluation:

Relevance of Resource Efficiency indicators and their need for further development

	resource efficiency	resource use	env. impact quantity	env. impact quality and ESS
energy	GDP/GIEC (ter.)	TPES (ter.)	fuel use / natural stock	fuel use / quality of stock
	GDP/TNEC (res.)	total net energy consumption (TNEC) (res.)		
		FEC (ter.)		
		total energy requirements (res.)		
		import dependency (imp/TPES) (ter.)		
		import dependency (imp/TNEC) (res.)		
		renewables / TPES (ter.)		
		renewables / TNEC (res.)		
		energy footprint		
materials	material productivity (GDP/DMC)	DMC	EMC	
	material productivity (GDP/RMC)	DMI	macro LCA	
	material productivity (GDP/TMC)	RMC	mat.use / nat. stock	
		RMI	fish catch outside safe biol.limits	
		TMR		
		TMC		
		PTB		
		RTB		
		import dependence (imp/DMC)		
water	water productivity (GDP/water appropriation)	water abstraction	WEI	available freshwater resources
		water consumption	WEI +	Chlorophyll in coastal + marine waters
		water footprint	urban waste water treatment	nutrients in freshwater
land	land productivity	artificial land or built-up area	Ecological Footprint	carbon content in soils
	forest fellings / net increment	Land Footprint; ALD	fragementation of ecosystems	species diversity
			(gross) nutrient balance (N and P)	designated areas
			soil erosion	common bird index
			HANPP	
			eHANPP	
CO2 emissions	CO2 emission intensity	Greenhouse gas emissions	concentration of atmospheric GHG	change in temperature
	GHG emissions intensity	CO2 emissions (ter.)		
		carbon footprint		
wastes, other emissions	air emission intensity	emissions from landfills		exposure of ES to acidification
	waste intensity	Other air emissions		exposure of ES to eutrophication
	recycling rates	total recycling amounts		exposure of ES to ozone
		total waste generation		air quality in urban areas
		landfills / artificial land		

Legend: Colour codes: green (criterion completely fulfilled), yellow (criterion partly fulfilled), red (criterion not fulfilled). Colour of font: relevance to resource efficiency (R). Background colour of cell: evaluation of need for further development (ACER – acceptability, clarity, easiness, robustness)

Abbreviations: res.: resident principle (i.e. global perspective), ter.: territorial focus (i.e. domestic perspective), GDP: Gross Domestic Product, GIEC: Gross Inland Energy Consumption, TPES: Total Primary Energy Supply, TNEC: Total Net Energy Consumption, FEC: Final Energy Consumption, DMC: Domestic Material Consumption, DMI: Direct Material Input, RMC: Raw Material Consumption, RMI: Raw Material Input, TMR: Total Material Requirements, TMC: Total Material Consumption, PTB: Physical Trade Balance, RTB: Raw Material Trade Balance, EMC: Environmentally Weighted Material Consumption, WEI: Water Exploitation Index, ALD: Actual Land Demand, HANPP: Human Appropriation of Net Primary Production, eHANPP: embodied Human Appropriation of Net Primary Production, GHG: Greenhouse Gases, ES: Ecosystem Services.

Proposed set of headline Resource Efficiency indicators:

	resource efficiency	resource use	env. impact quantity	env. impact quality and ESS
energy	GDP or WB / TPES (ter.)	TPES (ter.)	fuel use / natural stock	fuel use / quality of stock
	GDP or WB / TNEC (res.)	total net energy consumption (TNEC) (res.)		
materials	material productivity (GDP or WB / DMC)	DMC	EMC	
	material productivity (GDP or WB / RMC)	RMC	mat.use / nat. stock	
water	water productivity (GDP/water appropriation)	water abstraction	WEI	
		water footprint	WEI +	
land	land productivity	artificial land or built-up area	(gross) nutrient balance (N and P)	species diversity
		Land Footprint; ALD	HANPP	
			eHANPP	
CO2 emissions	CO2 emission intensity	CO2 emissions (ter.)	concentration of atmospheric GHG	change in temperature
	GHG emissions intensity	carbon footprint		
wastes, other emissions	recycling rates	total recycling amounts	exposure of ES to acidification	
	air emission intensity	Other air emissions	exposure of ES to eutrophication	
	waste intensity	total waste generation	exposure of ES to ozone	
			macro LCA	

Legend: WB = Wellbeing which stands for a beyond GDP indicator to be developed in WP 8
Colour codes: green (criterion completely fulfilled), yellow (criterion partly fulfilled), red (criterion not fulfilled). Colour of font: relevance to resource efficiency (R). Background colour of cell: evaluation of need for further development (ACER – acceptability, clearity, easiness, robustness)

Abbreviations: res.: resident principle (i.e. global perspective), ter.: territorial focus (i.e. domestic perspective), GDP: Gross Domestic Product, WB: Wellbeing, TPES: Total Primary Energy Supply, TNEC: Total Net Energy Consumption, DMC: Domestic Material Consumption, RMC: Raw Material Consumption, EMC: Environmentally Weighted Material Consumption, WEI: Water Exploitation Index, ALD: Actual Land Demand, HANPP: Human Appropriation of Net Primary Production, eHANPP: embodied Human Appropriation of Net Primary Production, GHG: Greenhouse Gases, ES: Ecosystem Services