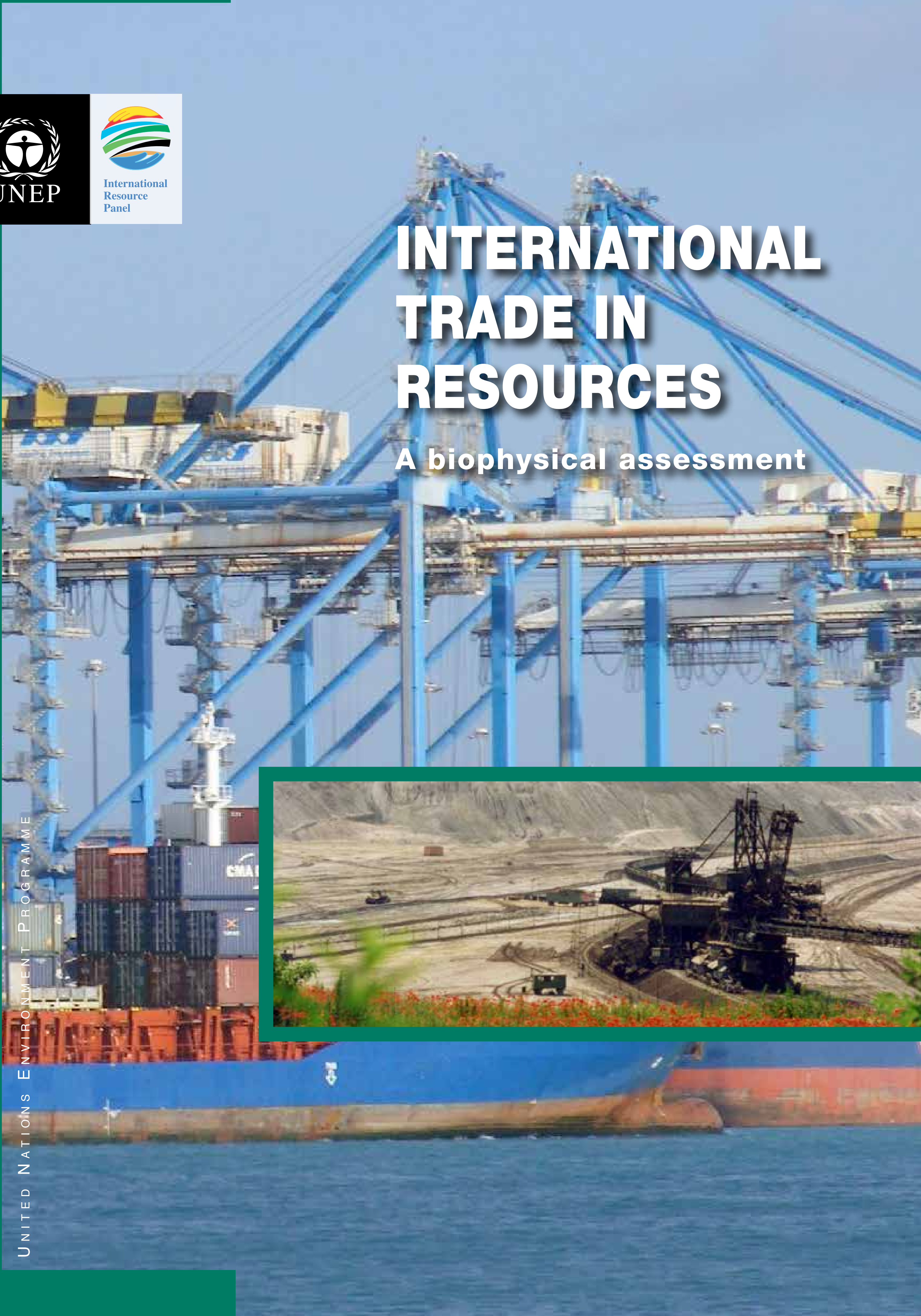
UNEP

International Resource Panel



INTERNATIONAL TRADE IN RESOURCES

A biophysical assessment

United Nations Environment Programme

Acknowledgements

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UNEP

International Resource Panel

UNEP Trade Report

INTERNATIONAL TRADE IN RESOURCES

A biophysical assessment

Produced by the International Resource Panel

Prepared by

Marina Fischer-Kowalski, Monika Dittrich, Nina Eisenmenger, Paul Ekins, Julian Fulton, Thomas Kastner, Karin Hosking, Heinz Schandl, Jim West, Thomas O. Wiedmann

'Draft design of Final Report for Launch Event Only'

Preface

World trade has expanded vastly over past decades, fuelled by progressive liberalisation and rapidly increasing demand for resources. Between 1980 and 2010 the value of trade increased more than six-fold and the volume of trade more than doubled in order to meet the needs of a growing and more prosperous global population.

Increased trade is indispensable in overcoming localised limits to the supply of natural resources. However, it is precisely the corresponding impact it has on raising global production and consumption which is worrisome from an environmental standpoint. Trade also raises distributional concerns, by shifting environmental problems related to extraction and processing activities from high-income importing to low-income exporting nations.

Tasked with building and sharing knowledge on how to improve management of the world's resources, UNEP's International Resource Panel (IRP) turns its attention to the world trading system and its implications for global resource efficiency. In this report entitled ''*International Trade in Resources: A biophysical assessment*'', the IRP examines how efficient the current system of world trade is in distributing resources from the geographical locations of supply to the locations of demand. By examining trade from a biophysical (versus an economic) viewpoint, the authors of the report seek to assess whether or not trade allows commodities to be obtained from countries where their production requires fewer resources and generates a smaller amount of wastes and emissions.

The particular report was prepared by the IRP's Working Group on Environmental Impacts, with the aim to enhance knowledge on the nature, location and size of the environmental impacts of trade. It provides a comprehensive synthesis of the latest scientific evidence on the ''upstream resource requirements'' of international trade. These refer to the materials, energy, water and land used along the production chain of traded commodities, and function as a proxy for the ecological effects of trade.

By reviewing the existing literature on the topic, the authors hope to aid understanding of the complex inter-relationship between trade and environment. In doing so, they seek to provide answers to a series of questions relating to the degree and distribution of trade dependency; the magnitude and composition of upstream resource requirements; as well as the implications of trade for global resource efficiency.

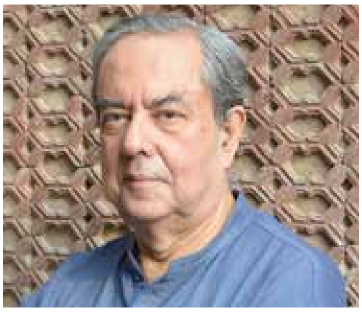
The study highlights the heightened vulnerability of the global trading system, as its balance relies on ever fewer resource producers.

With regards to estimating upstream resource requirements, the report draws attention to the difficulties involved. Estimates of upstream materials, water and land range widely, from 40 to 400 per cent of traded materials, depending on methodology and resource. Nevertheless, some common conclusions can be drawn. For instance, accounting for upstream resources embodied in trade accentuates patterns of unequal exchange, as the difference in resource use between developed countries and developing countries becomes much more pronounced.

As for the central question of whether international trade improves or worsens the efficiency of global resource use, the answer remains inconclusive. Yet, the fact that upstream requirements have been shown to be rising over-proportionally in recent decades, means that there are likely other factors which prevent a potentially more environmentally efficient allocation of resources through international trade.

On the whole, the report contributes to the discussions on resource use and resource efficiency. It presents an authoritative, policy-relevant assessment that sheds light on the implications of global trade for environmental sustainability and resource scarcity. It provides knowledge required by policy-makers to help tackle the negative environmental consequences of trade and craft trade policies in support of environmental objectives.

Dr. Ashok Khosla,
New Delhi, India



Dr. Janez Potočnik,
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September 2015

Foreword

International trade has long been recognized as an important enabler of economic growth and prosperity, permitting countries to meet rising demand for resources that are not available or affordable domestically. Benefits such as increased production, cost efficiency, competition and choice are evident, but their environmental impacts are more ambiguous. A better understanding of the complex interactions involved is needed to shape policy that can maximize synergies and minimize trade-offs, particularly given the recent surge in trade flows.

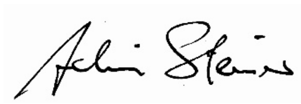
"International Trade in Resources: A biophysical assessment" makes a significant contribution to this understanding. While examining trends in the international trade of natural resources, it focuses on upstream requirements such as materials, energy, water and land used at the point of extraction or production. This approach is useful because it takes account of the additional resources consumed in the country of origin and the waste and emissions left behind once the goods are exported.

Looking back over the past three decades, the report provides evidence of the rising upstream requirements due to a general increase in trade levels, a greater share in the trade of high-processed goods, declining metal ore grades and the need to feed a growing population from land with diminishing productivity. It concludes that these factors are likely to offset any potential resource efficiency and environmental benefits associated with extraction and production processes.

Although there is no definitive conclusion as to whether trade improves or worsens the global efficiency of resource use, its distributional impacts are more apparent. Trade typically shifts the environmental burden from high-income and densely populated importing countries to low-income and more sparsely populated exporting countries. The extraction and processing of resources for export depletes natural assets, while increasing waste, emissions, loss of biodiversity, land degradation and water pollution. Likewise, domestic efforts to curb greenhouse gas emissions in one country may be negated by increasing imports from, and transferring investments, to countries with weak legal commitments to reduce emissions.

However, such damaging impacts on the environment can be limited by clear policies, bilateral or regional trade agreements, border adjustment mechanisms, and subsidies and free emissions allowances for domestic firms.

Therefore, while explicit policy analysis is beyond the scope of the report, it provides essential knowledge for anyone seeking to develop a supportive policy framework that can increase both trade and environmental benefits, through efficient production, resource management and access to green technologies and goods.



Achim Steiner
UN Under-Secretary-General
UNEP Executive Director

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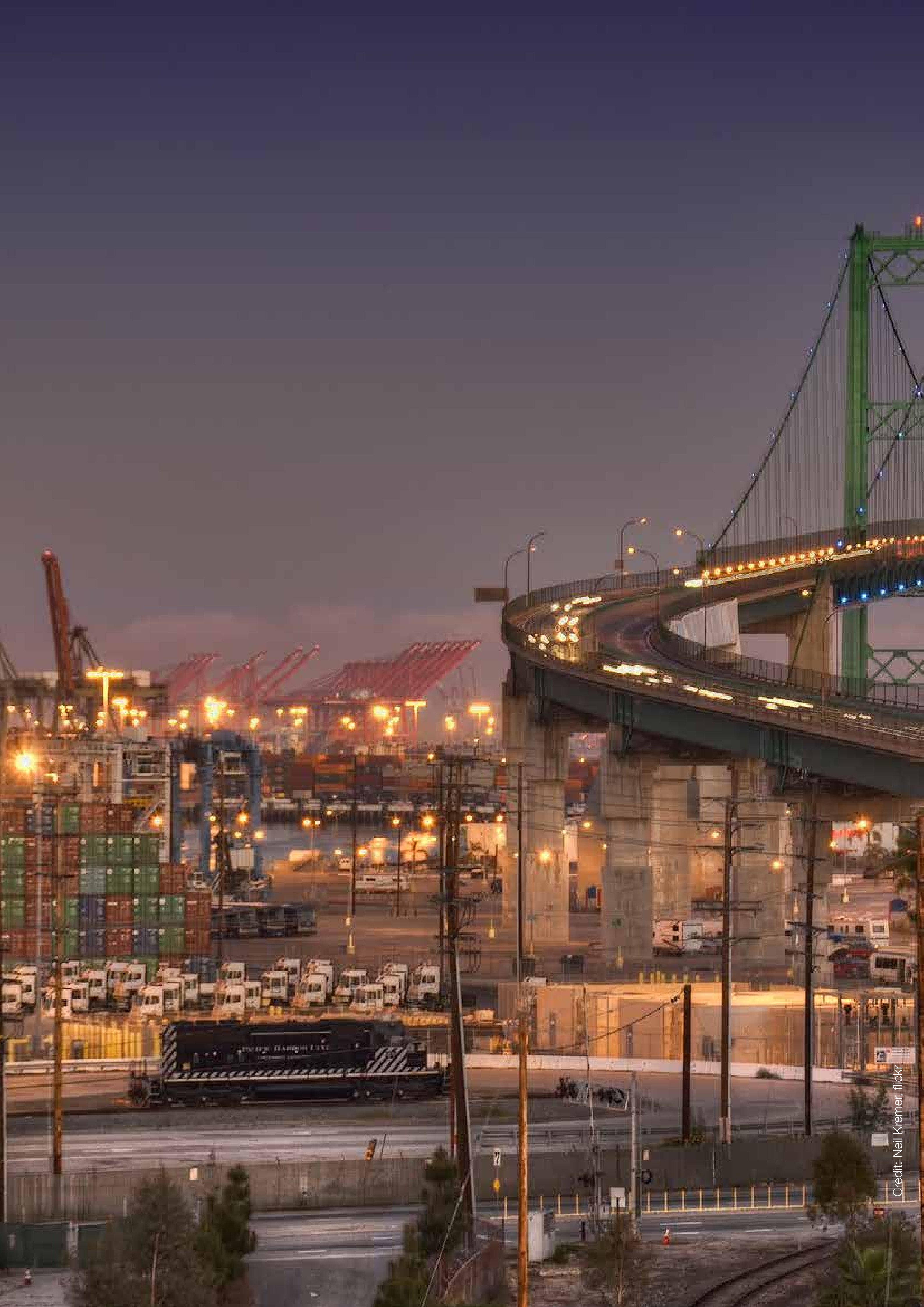


Credit: Neil Kremer, flickr

1. Introduction

The availability and quality of natural resources such as energy, materials, water and land are essential to human well-being and sustenance. The uneven distribution of these resources, owing to geological or climatic factors among others, has traditionally led to human settlements in geographies where the required resources were plentiful and accessible. If resources were plentiful, the settlement process created population centres, which often turned into industrial regimes dependent on the immediate natural environment of resources. The resulting depletion in local availability created a demand for resources from peripheral territories. This pattern holds for renewable resources (e.g. forests, drinking water and food crops) and even more so for non-renewable resources (such as silver, copper, iron, coal and petroleum), which play a central role in the later stages of development. In physical terms, therefore, there is an inevitable asymmetry between population centres and peripheries: peripheries extract raw materials from nature and process them to a certain degree for their own consumption, on the one hand, and for use by the centres on the other. Centres have few raw materials to extract, but they process the extracted raw materials further and consume them, and deliver manufactured products to the peripheries. Historically, urban centres have specialized in commodities for which resources were easily accessible within their peripheries, and exchanged them, through trade, for specialized commodities from other centres (Pomeranz and Topik, 2006).

The evolution of international trade has facilitated the transfer of resources from the centres of supply to the centres of demand. But how efficient is the current system of world trade in distributing resources? Often, economic efficiency, determined by the relationship between monetary costs and benefits, is used to measure the efficiency of world trade. In recent times, however, resource and environmental efficiency is gaining prominence as a determinant. Resource and environmental efficiency is about the relationship between the amount of resources and environmental impacts and a certain service: the fewer the resources and environmental impacts, the more efficient the service is. The indicators that give insights into economic efficiency are monetary. The indicators of resource and environmental efficiency are physical, with the former often being measured by means of material flow analysis (MFA), and the latter by life cycle assessment (LCA) and related methods.

This report focuses on resource and environmental efficiency more than on economic efficiency. From a global perspective, international trade would be considered resource efficient if resources were extracted and commodities were produced where the least environmental pressure is exerted.Theoretically, insofar as external costs are internalized, international trade gives rise to resource transfers in which the environmental burdens and losses associated with resource extraction and use are taken into account. However, as long as resource and environmental issues are considered as external costs, the agendas for economic efficiency, on the one hand, and resource and environmental efficiency, on the other, will continue to diverge.

Even as economic and environmental limits to the supply of a number of resources become visible, demand is set to escalate significantly in the future, as our assessment will demonstrate. Increasing world trade is one way of overcoming local and regional supply shortages and balancing supply and demand. It is clearly desirable that resources should be used efficiently, but limits to supply remain and efficiency by itself cannot address distributional issues within or between countries, or in respect of future generations. Thus, apart from resource efficiency, this report will also focus on a number of additional questions, which may be closely related, pertaining to the structure of and changes in world trade, questions such as:

1. How important is trade for supplying countries with resources? How is trade dependency distributed, and how does it vary between resources and change over time?
2. What are the upstream resource requirements, in terms of materials, water, land, and energy, of traded commodities? How large are these requirements, how are they composed and how do they change over time?
3. How are the roles in the world market organized, where are the centres of use and demand, and where are the locations of supply for resources? How do these factors vary between resources, and in what way do they change over time?

These questions may be, and indeed have been, approached from a number of different perspectives, in which economic analysis and implications tend to predominate (e.g. UNCTAD, 2013). This report pursues a different track, stressing and exploring the biophysical dimension of international trade, and building on, developing and applying earlier work in this vein (e.g. Bruckner *et al.*, 2012; Dittrich *et al.*, 2012; Dittrich and Bringezu, 2010; Hertwich and Peters, 2009; Lenzen *et al.*, 2013; Muñoz *et al.*, 2009; Schoer *et al.*, 2012; Steen-Olsen *et al.*, 2012). The economic and biophysical perspectives of international trade are intertwined, and finding solutions to global resource and environmental problems will need to build on both biophysical and monetary perspectives. However, given the rapid rise in the number of assessments and reports on international trade from an economic perspective (Dobbs *et al.*, 2013; Lee *et al.*, 2013; UNEP, 2013; World Bank, 2014a), the International Resource Panel (IRP) has explored issues from a biophysical perspective (Fischer-Kowalski et al., 2011).

The scientific literature on trade-related *physical* flows is expanding rapidly, particularly since a number of environmentally extended multi-regional input-output models (MRIOs) allow national material consumption to be traced through international trade flows to the regions of origin of the required inputs. New indicators such as "material footprint" and "water footprint" have emerged and allow the material (or carbon, or water, or land) consumption levels of individual countries, including the upstream flows used to produce respective imports and exports, to be characterized (see Hoekstra and Wiedmann, 2014; Tukker *et al.*, 2014; Wiedmann *et al.*, 2013). As comparative assessments have demonstrated (Inomata and Owen, 2014; Moran and Wood, 2014; Schaffartzik *et al.*, 2014a), the outcome of these calculations still depends strongly on the background assumptions made and the MRIO model used; it will take some time before methods are sufficiently harmonized to yield fully reliable results.

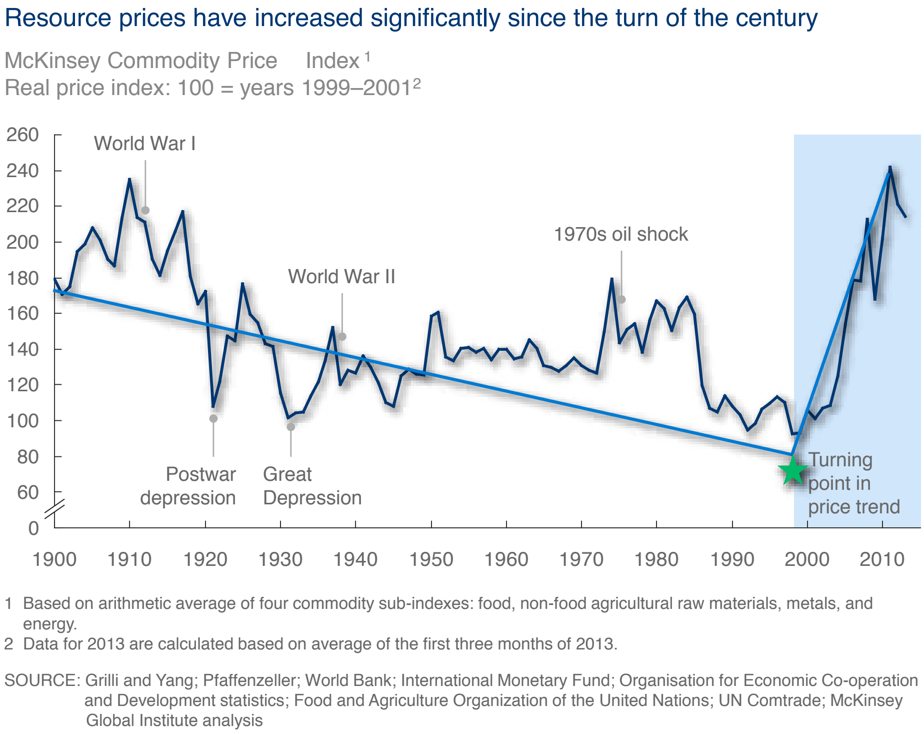
In this context, our report seeks to assess the existing (and often very recent) literature for an overview of approaches and findings, and to help answer certain questions outlined in this Introduction. As it will focus on physical trade flows, such as direct flows and upstream flows of materials, water and land, we begin with a sketch of the changed economic context, and then briefly explain why the observation of physical flows delivers specific insights different from those obtained from the more common types of economic analysis.

1.1 The economic world context: rapidly growing resource demand, potential supply shortages and rising prices

As shown in a previous report *Decoupling natural resource use and environmental impacts from economic growth* (UNEP *et al.*, 2011), the global use of natural resources has risen substantially, particularly since the start of the twenty-first century. The accelerated rate of resource extraction coincides with a change in the price system: the prices of natural resources steadily declined in the twentieth century; however, the price increments since the beginning of the twenty-first century have more than compensated for the centennial decline (Figure 1).

Figure 1

Raw material prices throughout the twentieth century and beyond



Source: (Dobbs *et al.*, 2013, p. 6)

As Dobbs *et al.* point out in *Resource Revolution: Tracking global commodity markets. Trends survey 2013* (Dobbs *et al.*, 2013), this is a structurally new situation, which they expect to last and which creates a "changing resource landscape" with the following features (p.6ff):

- rising and more volatile resource prices – newer sources of resources are costlier to access because of the accelerating depletion of supplies

- an increasingly close correlation between resource prices, owing to interdependencies and substitutions
- water shortages that threaten resource extraction across a variety of resources.

Consequently, there is an urgent need to address not only distributional questions relating to fairness and efficiency but also the growth in resource use. In economic terms, global trade has been recognised for its contribution to boosting production and consumption in industrial and developing countries. Environmentally, however, its contribution and the impact of its growth are ambiguous. The coincidence between high global economic inequality and international trade foster a situation of exploitation of resources (and of people) at a high rate and for an unsustainable benefit (Alsamawi *et al.*, 2014). The process of outsourcing the world's textile production to some of the world's poorest countries is an example of this phenomenon. Extremely low wages in poor countries allow people in high-income countries to buy these garments at very low prices, and subsequently to buy considerably more than they would, if these garments were produced at their own wage rates. Although this is considered to be economically efficient, it has an adverse impact with regard to human health, land-use, the use of chemicals, water pollution and emissions, especially in the manufacturing countries. According to Schor (2005), the "global sweatshop" and international trade combined contribute to over-consumption, the wasting of natural resources and environmental pollution. While these complex and controversial questions will not be at the centre of the analyses presented in this report, the close nexus of socio-economic and environmental issues is important in the search for solutions.

"High prices [of natural resources] and increased volatility suggest critical linkages between environmental sustainability, geopolitical stability and economic prosperity, making these goals harder to achieve in the absence of integrated and coordinated responses at the international level. Are we on the cusp of a new world order dominated by struggles over access to affordable resources?" (Lee *et al.*, 2013).

1.2 The monetary and physical representation of the life cycle of resource extraction, processing, consumption and deposition

Understanding the dynamics between weight and value during a product's life cycle is key to understanding the difference between a monetary and a physical representation of trade flows. At the beginning of a product's life cycle – during the extraction phase – the weight of the sum of all required inputs is at a maximum, while the value of these inputs is low. With each step in the life cycle, a part of the inputs is processed and transformed into wastes and emissions, and the product itself becomes lighter in weight. At the point of sale for consumption, only an estimated average 15 per cent of the original weight is contained in the product,[1] while the product's value is at its maximum. During the use phase, both weight and value tend to decline; when use ends, the product is either dissipated (e.g. burned) or discarded, and its value reduces to zero (see Figure 2).[2] These opposing trends of physical and monetary flows have also been shown by Clift and Wright (2000) for environmental impacts and added value.

1 This percentage, of course, depends on the reference indicator. If it refers to "total material requirement" (TMR) as in Figure 2, its weight at the point of sale for consumption is roughly 15%. If it refers to "domestic extraction" (DE) that only encompasses used extraction (i.e. ores or biomass harvests), as shown in Figure 2 at the second stage in the life cycle, then products at the point of final consumption amount to about 30% of DE (Bringezu and Bleischwitz, 2009; Haas *et al.*, 2015).

2 If it contains recycling material, its value may still be positive; if it gives rise to waste management costs, its value may even be negative.

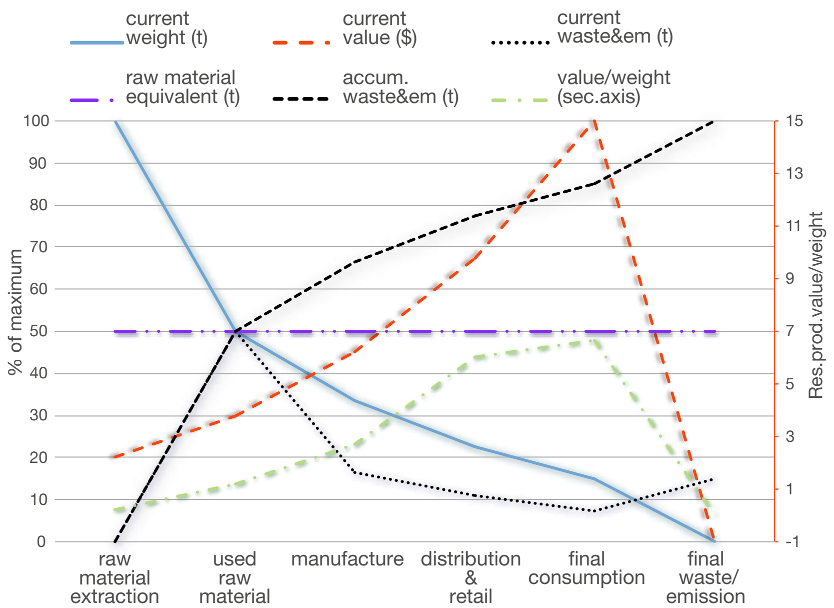
Monetary values alone are not sufficiently extensive to enable an assessment of the environmental burdens of traded materials. However, physical flows analysis is a complex undertaking. Each kilogram of traded materials is part of a long value chain, along which the resources used generate different environmental burdens. Moreover, the materials along the value chain are frequently traded several times, which could entail a problem of double counting.

At the extraction stage, there are two environmental burdens to be considered: the gradual depletion of the source (in the case of non-renewables) and the possible reduction in production potential (in the case of renewables). Depreciation of resources is expressed in economic terms and the substitutability of natural capital by man-made capital is mostly supposed.[3] Physically, for non-renewable resources (such as metals and fossil fuels), statistical sources show that reserves tend to increase in pace with extraction (production). However, it is safer to assume that ultimate physical limits to exploitable natural resources exist and to conclude that the greater the extraction, the sooner the source will be depleted. Indicators such as “Genuine Savings” (World Bank, 2003) and “Inclusive Wealth” (UNU-IHDP and UNEP, 2012)”event-place”:”Cambridge”,”author”:[{“family”:”UNU-IHDP”,”given”:””},{“family”:”UNEP”,”given”:””}],”issued”:{“date-parts”:[[“2012”]]}}],”schema”:”https://github.com/citation-style-language/schema/raw/master/csl-citation.json”} have been proposed to assess the risk of foregoing a site’s natural capital and the future benefits it may provide. For renewable resources like biomass, significant issues include the relationship between the rate of extraction and the rate of regeneration, and the secondary effects of habitat destruction and biodiversity loss (Lenzen *et al.*, 2012). Hence, all other things being equal, high levels of extraction generate a high environmental burden.

3 See a recent critique of these indicators by the EU-FP7 project *Welfare, Wealth and Work for Europe* (van den Bergh and Antal, 2014).

Figure 2

Material use, wastes and value added along a product life cycle from extraction, across production, consumption and deposition



Model assumptions: from raw material extraction to used raw material, 50% of material is discarded (difference between TMR and DE); at each further stage, 33% of weight is lost to wastes/emissions. From one stage to the next, the value increases by a factor of 1.5, but drops to zero after consumption (stylized facts). The raw material equivalent (RME) corresponds to used raw material (DE) (see Haas *et al.*, 2015).

The production of wastes and emissions is a critical environmental burden determinant during the extraction phase and in later processing stages. For a typical product, the share of wastes and emissions at the extraction stage is estimated to be roughly 50 per cent[4] of all the wastes and emissions that will occur along the full life cycle. Additional wastes and emissions occur along the remaining production chain, and the product itself becomes lighter at each stage (compared to the volume of all the materials used to produce it).

The logic for materials illustrated in Figure 2 also applies to water, except that water is rarely traded in big quantities directly between countries. The downward slope for materials in Figure 2 is pertinent to water, as more water is required (e.g. in mining and agriculture) during the extraction stages of the life cycle than at further stages of production. Land differs from both materials and water as a resource in that it cannot be traded physically on domestic or international terms and hence is always 'embodied' in resource consumption. Land resources are largely linked to primary production, i.e. the cultivation of crops and the growing of wood. Greenhouse gas (GHG) emissions are not traded physically either, as they occur along production chains.

The wastes and emissions that have accumulated up to the stage being observed (for example, when a commodity is traded) are equivalent to the "upstream requirements" of the commodity at that stage (see "accumulated wastes" in Figure 2). The 'raw material equivalent' of the commodity will be the sum of its current weight plus the weight of the upstream requirements that have been transformed into wastes and emissions. The 'raw material equivalents' (RMEs) follow the chain upward to 'used raw material' (equivalent to domestic extraction, DE), and along the 50 per cent level that separates used extraction from the 'unused extraction' included in the 'total material requirement' (TMR) (for methodological explanations see Fischer-Kowalski *et al.*, 2011). Wiedmann *et al.* (2013) propose the term "material footprint" to denote the amount of materials consumed in a country including their upstream raw material equivalents. For water, these are mostly called "virtual flows" (see Chapter 3 of this report for further explanation).

In the use phase of a product, resources are considered as accumulated quantities of "stocks in use" and as waste deposits that may one day become sites of 'urban mining'. As urban agglomerations are spatially concentrated, energy and materials use is of very high density, with potential side effects in terms of increased local and regional pollution, noise pollution and material turnover. The wastes and emissions flows at this stage are of the same magnitude as the flows of the products.

Centres specialising in the distribution, retail and consumption end of the extraction-consumption chain - by importing goods - face relatively less depletion of their resources, and consequently lower amounts of the wastes and emissions associated with the production process.

The monetary value along the same chain, in contrast, has an upward slope: at each stage there is more capital and labour added, increasing the value of the product. At the final stage, irregularity of economic value, as stated by Ayres and Kneese (1969), is observed: the economic value of a product disappears post-consumption (it may even turn negative for the cost of disposal), while physically things follow the law of conservation of mass. Apart from this irregularity, traded products increase in value (i.e. \$/kg) as they move further along the extraction–consumption chain. The relationship between value and weight as a measure of resource productivity takes a similar, irregular course. Resource productivity increases along the life cycle up until the point of sale, and then declines gradually, possibly to below zero at the end of the product's life when it is discarded as waste. Thus we infer that locations primarily specializing in resource extraction tend to display low levels of resource productivity (as measured in GDP per unit of domestic material consumption), in contrast to the high levels of resource productivity in locations where consumption occurs. This must not be mistaken for technical efficiency, but simply results from the opposing trends in weight and monetary value. At least part of this bias in resource productivity is removed

4 See footnote 1 above. The 50% refers to the difference between TMR and DE (see Bringezu *et al.*, 2004). The loss from used extraction to each subsequent stage is, on average, assumed to be 33% of DE. Even if we assume a constant share of waste and emissions at every stage of the chain, absolutely speaking, 33% waste of the total resource input (=100%) amounts to much more than, say, 33% of the 67% in useful parts that proceed to the next stage (see Haas *et al.*, 2015).

when the indicator is expressed as GDP per unit of Raw Material Consumption (RMC), or, in the terminology of Wiedmann *et al.* (2013), per material footprint.

It is important to emphasize here that the explanations above are not for technical efficiency, but an inference of the opposing trends in weight and monetary value along the extraction-consumption chain of a product.

Hence, despite the strong link between them, physical and monetary aspects reveal different trends. Figure 2 illustrates the background dynamics to bear in mind when comparing national economies dominated by different stages of the life cycle (Haas et al, 2015).

On the other hand, trade balances follow an inverse logic: in the economic sense, a country's trade balance is positive when the value of its exports is higher than the value of its imports; in the physical dimension, a country's trade balance is positive when the weight of its imports is higher than the weight of its exports. Therefore, countries which export high-weight (but low-price) raw materials and import low-weight (but high-price) commodities will tend to have both a negative monetary and a negative physical trade balance. Some Latin American countries are an example of this trend, such as Argentina between 1992 and 2000, Mexico between 1997 and 2012, and Brazil between 1995 and 2001 and again from 2009 until 2011. In contrast to this, countries that mainly import raw materials and export manufactures – such as some in southeast Asia – tend to demonstrate positive monetary trade balances but negative physical trade balances. This shows that physical and monetary descriptions of trade processes look very different, and that physical accounts provide very specific information.

1.3 Scope and structure of the report

This report is an assessment of the scientific literature on the biophysical features of international trade, and the implications of the current trade system for efficient and environmentally considerate use of the world's natural resources. It refers to material resources (biomass, metals and minerals, construction minerals and fossil fuels), water resources and land resources. As an assessment, it depends on the time horizon of the primary literature. Although efforts were made to extend the observation period to the past 50 years, most of the analyses at least cover the period from 1980 to 2010. An assessment also depends on the differentiations (for example, regional aggregates or country selections) used in the primary literature; efforts to secure comparability did not always lead to fully satisfactory results.

The only primary database[5] we could access was the physical trade database built and maintained by Monika Dittrich, cited as Dittrich (2012).[6] This is based on United Nations Comtrade data (SITC-1 until 1993 and SITC-3 thereafter; UN, n.d.) and includes global accounts of imports and exports in physical (mass) units for 130, and later, 170 countries. All missing mass values in United Nations Comtrade were filled using the global annual price for each commodity group, starting at the most differentiated level, then summed up according to the classification structure. Values of direct trade flows of major outliers were corrected by adjusting the values with regard to global prices, amounts of global imports and exports and – as far as available – bilateral trade data as well as national and international sectorial statistics such as those from the United Nations Food and Agriculture Organization (UN FAO) or the International Energy Agency (IEA). Detailed methodological descriptions are given by Dittrich (2010) and Dittrich and Bringezu (2010).

5 However, another database created by Wiedmann *et al.* (2013) on the material footprints of nations 1990–2010 (http://www.pnas.org/cgi/doi/10.1073/pnas.1220362110) has since become openly accessible (http://worldmrio.com) and contains information on the Raw Material Equivalents of the imports and exports of all countries. For reasons of both time and resources, primary analysis of these data was not possible.

6 The physical trade database was developed by Dittrich at the University of Cologne and the Wuppertal Institute in Germany.

In order to calculate aggregates at regional and global levels, the original trade data missing from countries were estimated using extrapolation, bilateral data from trade partners and/or further sectorial, national and international trade statistics. In general, the United Nations Comtrade statistics for the majority of OECD and Latin American countries holds good with respect to differentiation and reliability, while for other countries the statistics are of mixed quality. The aggregated values of imports and exports and physical trade balances of 130 countries (in earlier years) and more than 170 countries (in recent years) covering the period from 1980 to 2010 are published at www.materialflows.net (www.materialflows.net; Dittrich, 2012).

There are several kinds of environmental pressure associated with traded goods during their life cycle: they range from the toxic emissions and wastes associated with certain stages of extraction/production to transport kilometres and the respective infrastructure and emissions involved, to land degradation, water abstraction and pollution. While life cycle assessment methods allow the generation of aggregate measures for (various) environmental pressures associated with the life cycle of a commodity, they are not always able to do so in a country-specific manner and in time series, in the way we have sought to do in this report. Other methods allow the assessment of aggregate amounts of upstream material flows linked to traded commodities (see Figure 2). A similar approach can be applied for upstream water use, energy use and CO_2 emissions, land and plant net primary production... In further sections of the report, we have used a combination of methods based upon material flow analysis, life cycle assessment and multi-regional input-output (MRIO) models to assess environmental pressures specified by country/region and time period; the methods are under development, and some are more mature than others. Although some allowance has to be made for certain constraints, a combination of methods enables an assessment of the resource efficiency of international trade and of how it changes over time, the basic assumption being that trade could be resource efficient, in that it allows commodities to be obtained from countries/locations where their production requires fewer resources and, consequently, generates fewer environmental impacts, compared to other production centres.

Infobox 1

Material Flow Accounting – methods and data

Material Flow Accounting (MFA) quantifies all material flows into and out of a socio-economic system that have been used in building or maintaining socio-economic stocks. The physical flows considered are all solid, gaseous and liquid materials, excluding water and air, measured in mass units (metric tons) (Eurostat, 2001; OECD, 2008). This biophysical representation of society-nature interactions is used to complement economic accounting systems.

Material Flow Accounting represents a broad family of different accounts from national to local level or from aggregate materials to single substances (OECD, 2008). Within this area, Economy-Wide Material Flow Accounting (EW-MFA) is the most widely applied method and a part of the standard statistical reporting in the European Union (2011). EW-MFA considers all material inputs and outputs of a socio-economic system, but treats the socio-economic system itself and any processes therein as a “black box”. Methodological harmonization and standardization has been vigorously promoted in the past few years, resulting in a high level of consistency among available datasets (Fischer-Kowalski *et al.*, 2011).

EW-MFA measures all the material flows that are required for the establishment, operation and maintenance of socio-economic biophysical stocks. By convention, these biophysical stocks include humans, man-made artefacts (infrastructure, buildings, vehicles, machinery, durable goods, etc.)

and productive livestock (animal husbandry and aquaculture). With respect to EW-MFA accounting, two system boundaries need to be defined: one between the socio-economic system and its natural environment, and another concerning the relationship to other socio-economic systems. With regard to the first boundary, material inputs are raw materials extracted from the domestic natural environment (domestic extraction, DE), and outputs are wastes and emissions released into the natural environment (domestic processed outputs, DPO). Flows crossing the second boundary are imports from and exports to other national economies. Following the laws of thermodynamics, in particular the law of conservation of mass, material inputs equal material outputs, corrected by stock changes (for more details, see Eurostat, 2001). Stock changes are material flows to socio-economic stocks with a lifetime exceeding one year, or materials released from physical stocks and transformed into wastes and emissions.

Domestic extraction (DE) is defined as the raw materials extracted from nature. DE includes agricultural harvests and forestry, as well as raw material extraction from mining and quarrying. Material flows are usually grouped according to four main material categories:

1. Biomass (harvested, plant-based biomass, i.e. crops, timber, grazed biomass, crop residues used, as well as animal biomass from wild fish catch and hunting. Biomass production from domestic livestock is not accounted as DE).
2. Metallic minerals (ores, accounted for as the mass leaving the mine, including the waste rock, i.e. “run-of-mine” approach).
3. Non-metallic minerals (minerals used in industrial processing or for construction purposes, such as sand, clays, phosphate, salt, diamonds, etc.)
4. Fossil energy carriers (coal, crude oil, natural gas, or non-conventional energy sources such as gas hydrate, shale gas).

Material extraction data are compiled from official statistics (i.e. agricultural statistics, mining statistics, production statistics, etc., (for details, see Eurostat, 2012). Some flows, such as crop residues, grazed biomass, or non-metallic minerals used for construction purposes, are only poorly or not reported at all in official statistics; in such cases, the extraction data have to be estimated using standardized MFA estimation procedures (Eurostat, 2013, 2009). In addition, gross ores often have to be estimated on the basis of metal concentrates reported in statistics and the corresponding ore grades (Eurostat, 2013).

Trade flows comprise products at different stages of processing, i.e. primary goods (copper ores or wheat), secondary products (copper wires or wheat flour) and final goods (mobile phones or cakes). During accounting for exports and imports in EW-MFA, goods are considered with their respective mass at the time of crossing administrative borders. The corresponding data source is foreign trade statistics, which report traded commodities in monetary and physical units.

To ascertain total raw material use in a country’s final consumption, all raw materials used in the production process of traded goods need to be considered. MFA summarizes these raw material inputs as the Raw Material Equivalents (RME; Eurostat, 2001; Schaffartzik *et al.*, 2014a) of traded goods. Adding (respectively subtracting) the RME of imports and exports to (or from) the domestic material consumption (DMC) yields the indicator Raw Material Consumption (RMC; Schaffartzik *et al.*, 2014a) or material footprint (Schoer *et al.*, 2012; Wiedmann *et al.*, 2013).

In the course of extraction, some materials are moved or extracted without the intention of using them in socio-economic processing or attributing economic value to them. These flows are commonly termed “unused extraction” and include unused by-products in agriculture (straw and roots left on the fields), by-catch in fishery, overburden in mining, or soil and rock excavated during the construction of infrastructure (Dittrich *et al.*, 2012; Eurostat, 2001). Often, no statistical data are available to account for unused extraction, and the mass of flows has to be estimated (Bringezu and Bleischwitz, 2009).

There are a number of MFA indicators (Eurostat, 2001; Fischer-Kowalski *et al.*, 2011), and the most prominently used among them are:

- Direct Material Input (DMI) = DE + imports.
- Domestic Material Consumption (DMC) = DE + imports – exports.
- Physical Trade Balance (PTB) = imports – exports.
- Resource Efficiency or Resource Productivity = GDP/DMC
- Raw Material Consumption (RMC) = DE + RME of imports – RME of exports
- Raw Material Trade Balance (RTB) = RME of imports – RME of exports
- Total Material Requirements (TMR) = DMI + RME of imports + unused extraction

Methods of calculating Raw Material Equivalents or upstream resource requirements

The development of methods of calculating RME has been rapid in the past 15 years, with several studies being published (Bruckner *et al.*, 2012; Giljum *et al.*, 2014; Muñoz *et al.*, 2009; Schaffartzik *et al.*, 2014a; Schoer *et al.*, 2013, 2012; Tukker *et al.*, 2014; Weinzettel and Kovanda, 2011, 2009; Wiebe *et al.*, 2012; Wiedmann *et al.*, 2013). Upstream resource use in trade is calculated primarily through two approaches: the first approach uses environmentally extended input-output models (IO) to trace inter-industry deliveries through the economy and between economies, down to final demand categories; the second approach uses coefficients from the life cycle inventories (LCI) of products, with which traded goods are multiplied in order to calculate the upstream material, energy, water or land requirements. These two approaches can be combined to form 'hybrid' LCA-IO approaches (for a discussion, see, for example, Schaffartzik *et al.*, 2014a). However, the systems reference of the two approaches is fundamentally different.

In the IO approach, the reference system of accounts is the national economy, and the amount and type of domestic extraction of resource materials in a specific year. These materials are then, with the help of monetary coefficients, allocated to final demand categories within the country and to its exports. At a global level, national IO tables have to be interlinked to create multi-region IO tables, as there is no comprehensive IO table for global level calculation (Tukker and Dietzenbacher, 2013; Wiedmann, 2009; Wiedmann *et al.*, 2011)2013; Wiedmann, 2009; Wiedmann *et al.*, 2011. This is a complex procedure and requires a number of assumptions that are not yet fully standardized. The same holds true for regional aggregates. However, in both cases, the same basic principle applies: resources extracted in the reference year are distributed top-down to meet final demand in various countries, and so the sum total of resources allocated to final consumption, and their composition, equals the sum total of resources extracted.

The choice of perspective – global or national – plays an important role in IO-based approaches. In material terms, a global perspective MRIO starts from global resource extraction and distribution of the resource to centres of final demand. All production processes are considered as one global production process. Under the MRIO approach, trade is reduced to extracted resources allocated to final demand in countries other than the extracting economy. Inter-industry trade that flows along the different steps of the production process are considered as internal flows and thus not counted as flows crossing the system boundaries of a nation state. In contrast, the national perspective includes all physical imports as physical system inputs processed within the economy in addition to resource extraction. The IO approach focuses on the amount of raw materials consumed by societies. It responds to the volume and type of resources connected to the final demand of a specific country in a specific year, and to whether these resources were (directly or indirectly) imported or extracted nationally. It allows direct trade flows to be expressed as "Raw Material Equivalents" (RME; Eurostat, 2001), that is, as the sum of materials directly traded plus their respective material upstream requirements.

For the LCA approach (Bringezu *et al.*, 2004; Dittrich *et al.*, 2012), the systems reference is the extraction-production-consumption chain of specific products or groups of products. The rationale of an LCA is to assess all environmental burdens connected to a product or service consumed in a certain country in a certain year, irrespective of where and when the service or product was produced. Since the early 1990s, significant efforts have been made to build LCA inventories for a broad variety of products and services, and to standardize procedures (Klöpffer, 1997). The original purpose of LCA was to guide comparisons between products and services across a standardized set of indicators for environmental burdens, particularly resource use. When LCA-based coefficients are used in the analysis of the upstream resource requirements of international trade, the analysis follows a bottom-up procedure with the respective national consumption as the point of departure. Owing to the complex international, inter-temporal and inter-product linkage of extraction-production-consumption chains, it cannot be guaranteed that the global sum total of resources used equals the sum total of resources actually extracted.

The LCA approach offers a 'cradle-to-grave' analysis of resource use. However, the further processing and use of traded commodities are usually not known; thus, 'cradle-to-product' coefficients for traded commodities account for upstream flows representing the process chain from delivery of the traded goods backward to primary production. A number of inventories assist in the calculation of LCA coefficients for products; these coefficients not only refer to the amount of materials used, but also, sometimes, to the associated unused extraction of primary resources (Bringezu, 2000). The approach has been widely applied on the product level, and a limited number of studies have analysed its application at the national level (Schütz *et al.*, 2004 for the EU; UBA *et al.*, 2008 for Germany). One global analysis has been published by Dittrich and colleagues (2012), covering trade between 1962 and 2010 in five-year steps.

The LCA approach differs from IO-based approaches in the following ways:

- The LCA-based approach used by Dittrich *et al.* (2012) and presented in this report also includes unused material extraction, i.e. overburden in mining, crop or harvest residues in agriculture and forestry, and by-catch in fishery. Soil erosion is also included as part of unused extraction.
- As the LCA approach analyses the relationship between imported goods (or product groups) and their respective volumes of upstream material use, it allocates all upstream requirements to the material category of the traded product. For example, the fossil fuel required to process a metal is assigned to the material group "metal ores". Hence the LCA approach does not classify upstream material use according to the material of origin.

Credit: Land Rover Our Planet, flickr

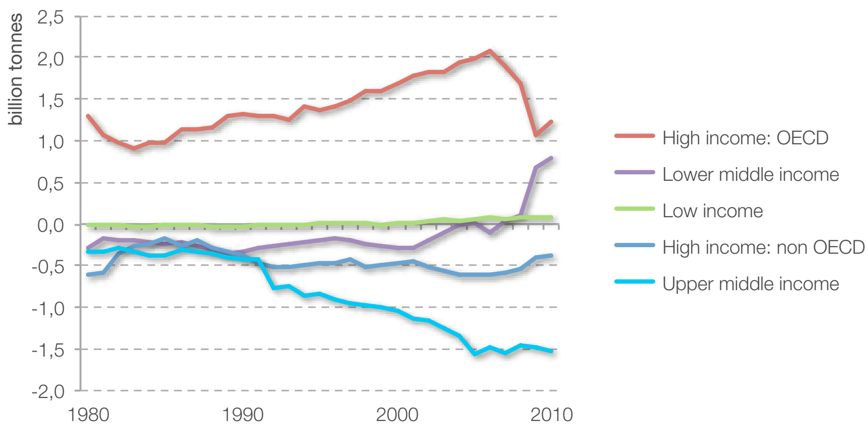
2. Trade in resources and commodities

2.1 Trade volumes are growing and with them the importance of trade

Rising global consumption, the industrialization of developing countries, globalization and the trend among many countries towards trade liberalization since the 1980s have led to a rapid increase in global trade during the second half of the past decade (Figure 3). While the volume of trade represents a 640 per cent increase when measured in monetary terms (UNCTAD, 2013), physical trade volumes grew more steadily, more than doubling in total between 1980 and 2010. A decrease in trade flows was observed twice: between 1980 and 1983, owing to the second oil crisis, and in 2009, owing to the global financial crisis. During the period in between, physical trade volumes increased by an annual average growth rate of 2.4 per cent.

Dynamics in trade, population, GDP, extraction and consumption, 1980–2010

Figure 3



Sources: data for monetary trade, GDP and population originate from the World Bank (2012); for physical trade,from Dittrich (2012); for extraction and consumption, from the online database www.materialflows.net (SERI, 2011)

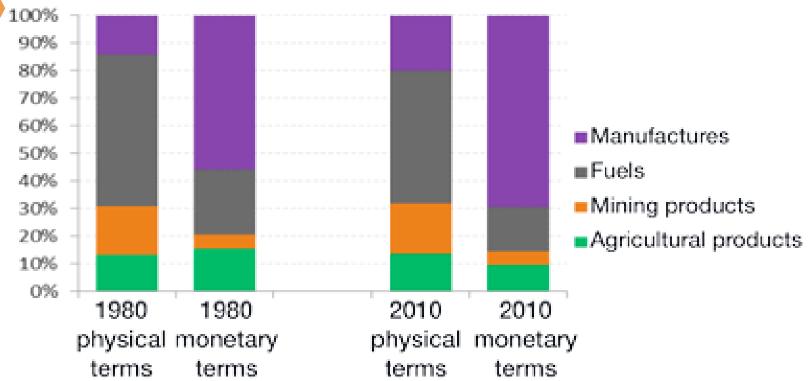
Through their dynamics, trade flows are significant for economic growth in GDP terms. Globally, on average, the share of exports in GDP was around 28 per cent in 2010 (compared with 19 per cent in 1980 (World Bank, 2012)). In physical terms, though, the volume of world trade rose by a factor of 2.5 from 1980 to 2011, while global resource extraction, representing global consumption in physical terms, less than doubled. Thus, world trade, in economic and physical terms, was more dynamic than global consumption. Until the global financial crisis, physical trade volumes increased twice as fast as material extraction. This increase was driven by a growth in the total amount of materials traded, in combination with a prolongation of production chains: the same material was traded several times, before it arrived at the point of final demand. Currently, around 20 per cent of global physical trade volumes arise from increasing specialization and the lengthening of value chains. Extraction, production and consumption continue to be primarily domestic: globally, nearly nine-tenths of total material extraction is consumed domestically, while one-tenth (12 per cent in 2008) is reallocated via international trade (Dittrich, 2010). However, when upstream material requirements of traded commodities are included, these statistics change. Out of the 70 billion tons of materials extracted globally in 2008, 40 per cent was extracted and used in the production of goods and services exported to other countries, even if part of those materials never left the country of origin (Wiedmann *et al.*, 2013).

Owing to the inverse trends in weight and value in the life cycle of products, as described in the Introduction, the composition of traded commodities looks very different in physical and monetary terms (see Figure 4): manufactured commodities dominate trade volumes in monetary terms, while fossil fuels hold the highest share of trade volumes in physical terms. In monetary terms, manufactures account for three-quarters of traded volume, whereas fossil fuels only represent 16 per cent (in 2010, see Figure 4). From a physical perspective, however, the picture is dominated by materials in the early stages of processing, in particular fossil fuels, which represent half of the traded volumes (48 per cent in 2010, Figure 4), while manufactures comprise only 20 per cent of traded volumes.[7]

7 These physical relations are particularly relevant when international transport is considered: here, of course, weights and volumes count. In the case of a substantial reduction of fossil fuel use, as demanded by climate policies, more than half of current international transport would disappear.

Figure 4

Shares of commodity groups in trade in physical versus monetary terms, 1980 and 2010



Sources: trade, monetary: WTO (2012); trade, physically: Dittrich (2012); assignation according to WTO (2012), where fuels, mining products and agricultural products include only primary goods. Further processed goods are aggregated under manufactures.

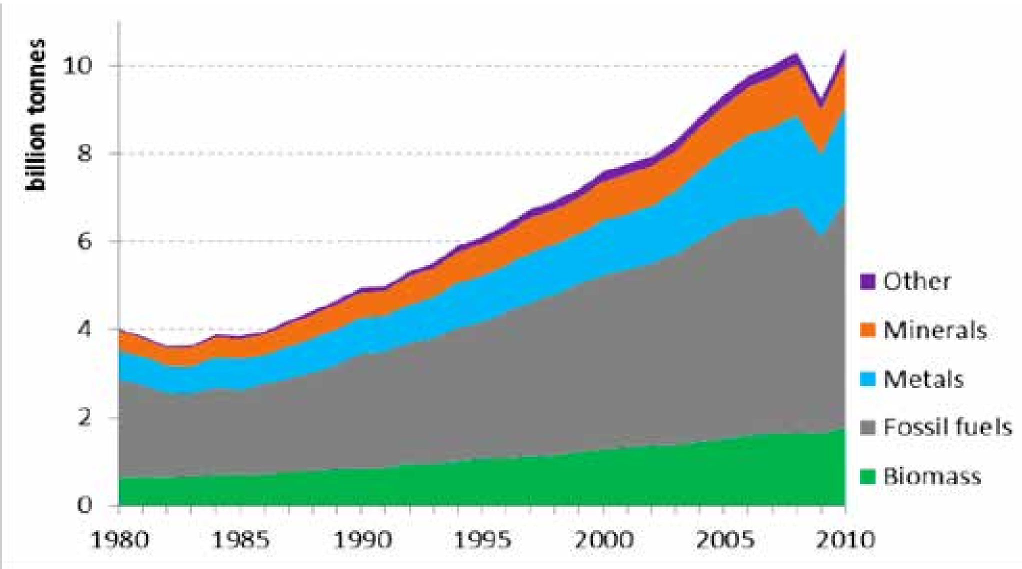
Current patterns of resource use show that global material extraction is mainly composed of non-metallic minerals used for construction purposes, such as sand, gravel, limestone, clays, etc. (SERI, 2011). These materials comprise 44 per cent of material extraction worldwide. Another 28 per cent is accounted for in biomass materials, followed by fossil fuels at 19 per cent. The material composition in trade, on the other hand, is different (see Figure 5). Fossil fuels make up half of the total trade, followed by metals and biomass. Non-metallic minerals play only a minor role in global trade.[8] Over the

8 This is very different when we consider upstream requirements of trade: built infrastructure (such as roads, harbours, buildings) and the materials required for them play a major role among the upstream requirements of traded commodities (Wiedmann *et al.*, 2013, p. 2)

past 30 years, traded volumes of all four material sub-categories have increased. As a result, the share of traded renewable (biomass) materials versus non-renewable materials (metallic and non-metallic minerals, fossil energy carriers) has remained fairly constant at around 16 per cent and 84 per cent respectively. The volume of fossil energy carriers trade is large, but its growth rates declined between 1980 and 2010. The share of fossil fuels in global trade dropped to 48 per cent in 2010 (compared to 56% in 1980). Trade in metals, on the other hand, increased significantly and reached a share of 20 per cent in 2010 (compared to 16 per cent in 1980).

Figure 5

Physical trade according to material composition, 1980–2010



Source: Dittrich, 2012; *measured as (imports + exports)/2.[9] In contrast to figure 4, the aggregation to the categories follows material characteristics as implemented in MFA. Thus, manufactures and higher-processed goods are allocated to the material categories according to the main material component (see also Eurostat, 2013).

9 Imports and exports represent all trade flows reported in foreign trade statistics. At a global level, the sum of imports should equal the sum of exports. Owing to some distortions and asymmetries in trade statistics, empirically this is not quite the case. This is why we measure the amount of traded volumes as (imports + exports)/2.

Through trade, resources are increasingly moved from the point of availability to the point of final demand, particularly resources such as fossil fuels and metals. Consequently, local resource scarcity no longer constrains population size or affluence and trade contributes to boosting consumption of all kinds of (locally unavailable) resources and resource use in general.

2.2 Suppliers and demanders in the world economy

Growth in resource use has been significant in past decades and has been accompanied by a growth in physical trade volumes. However, as centres of extraction and final consumption are often different, the following section aims to investigate the sources of supply and demand of resources among countries.

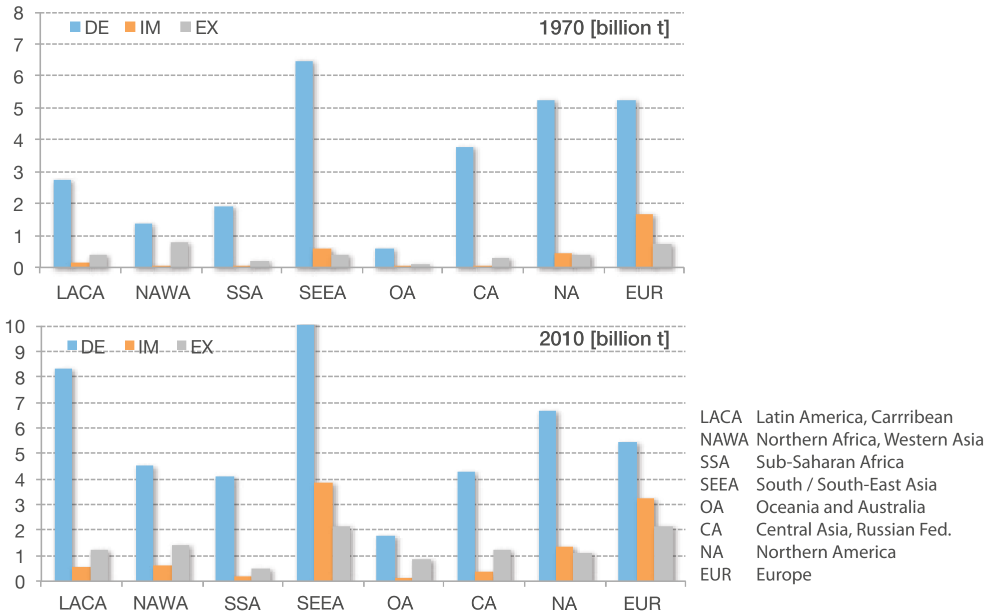
Resource extraction and trade

Resource extraction around the globe is highly diverse. Factors determining resource extraction include resource endowment and availability of space for extraction, and also historically evolved skills and technologies, colonial relations, longstanding interdependencies, mutual trade agreements, etc. As a result, countries and regions contribute different amounts and types of commodities to global markets, forming a functional differentiation in the global economy.

By 2010, all world regions were extracting and using more resources than in 1970 (Krausmann *et al.*, 2009). However, there were substantial differences in regional trends: while in mature industrial regions such as Europe, North America and the Russian Federation domestic extraction of resources hardly increased, in the remaining regions it doubled or tripled, or even increased five-fold, as seen in southern, south-eastern, and eastern Asia (Figure 6). In 1970, one-tenth of the global extraction was traded among countries (direct trade). In all regions, imports amounted to less than 10 per cent of domestic extraction and thus held low importance. Only Europe was importing one-third of materials in addition to domestic resources. Exports amounted to less than 15 per cent of domestic extraction, except for the oil-exporting regions of North Africa and Western Asia. Physical trade volumes increased significantly in the next 40 years. In 2010, 15 per cent of all globally extracted resources became part of direct trade, and 41 per cent was indirectly associated with trade (used in the production process, but not physically included in the traded goods). Imports now represent 15 per cent of domestic extraction globally. In North America and Europe, dependency on imports is significantly higher: in North America, imports amount to 20 per cent and in Europe up to 60 per cent of locally extracted resources. Major exporting regions today are Australia and Oceania, which export half of their resource extraction, North Africa and Western Asia, as well as Central Asia and the Russian Federation (30 per cent), and Europe (40 per cent).

Figure 6

Resource extraction, imports and exports by world region, 1970 and 2010



DE = Domestic Extraction, IM = Imports, EX = Exports. Regional imports and exports represent the total sum of imports and exports of the countries in the region; that is, intra-regional trade is included.

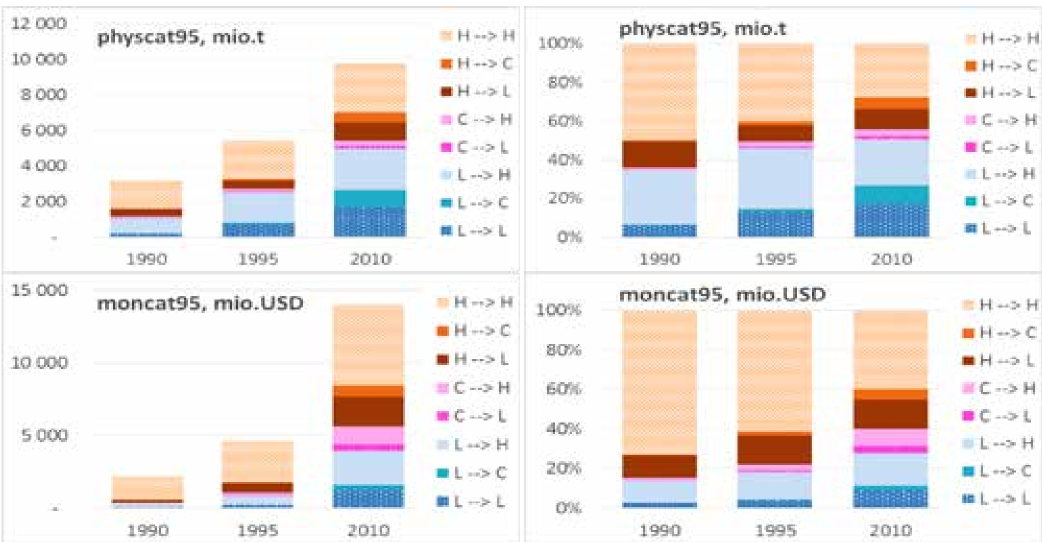
Source: (Schaffartzik et al., 2014b)

Europe demonstrates the highest trade dependency, with both a high demand for foreign resources and a high level of industrial production for exports. In part, though, this is a methodological construct because imports and exports represent the total sum of all countries in the region, including intra-regional trade. Europe consists of numerous relatively small countries often trading with one other, while the United States is a single country, comparable in size to the whole of Europe. In recent decades, Europe has been overtaken by south-eastern/southern/eastern Asia (SEA) with regard to exports (this occurred in the 1980s), but also with regard to imports in the 21st century. SEA is characterized by an extraordinary growth in imports and exports. In 2010, it was responsible for nearly half of the world's trade activities (see also, for example, Giljum *et al.*, 2011). SEEA countries together exported the highest volume of materials in all years, except during the second oil crisis (2010: 39 per cent of global exports). The SEEA trade dynamic is mainly driven by significant growth in the volume of trade of some large Asian countries (mainly China). The third-highest importing region is North America. In terms of exports, North America's rate is comparable to that of the other regions. Asia and Europe together are responsible for three-quarters of global trade flows.

Following the Second World War, trade was concentrated among the mature northern countries with imports from the South. Developing countries primarily acted as resource providers. During the 1980s, however, several emerging economies took steps towards trade liberalization and began entering the world market. This trend has become even stronger in the 21st century, making relations between the North and the South more symmetrical. In the Chatham House Report on Resources Futures (Lee *et al.*, 2013), the authors showed that the share of South-South trade doubled (measured in US Dollars) within a single decade and now amounts to almost one-third of global trade. The share of North-North trade, on the other hand, has shrunk, while exports from the North to the South are higher than ever before (Lee *et al.*, 2013). This dynamic was, to a large extent, driven by a strong increase in trade relations between countries in East and South-East Asia (UNCTAD, 2013, 2007; WTO, 2003).

Figure 7

The physical trade between countries grouped along income lines



Legend: Countries are classified by their income in 1995, according to World Bank. L= low, lower- middle- and upper-middle-income countries according to WB, H= high-income countries, C= China.
Source: Calculations by Peter P. Pichler and Helga Weisz, Data Source: UN Comtrade, DESA/UNSD (http://comtrade.un.org/db/)

An analysis of bilateral physical trade data was undertaken only recently by Pichler and colleagues (forthcoming) at the PIK in Potsdam; it supports the monetary trends presented in the Resource Futures report (Lee *et al.*, 2013). Figure 7 shows the physical trade between low-income countries (including middle-income countries), high-income countries and China (the latter was taken out of the group of low income countries in order to highlight its effect separately). Trade to China shows the highest growth rates between 1990 and 2010, and an increase by a factor of 28 in trade from high-income countries to China, and by a factor of 86 in trade from low-income countries to China. Trade from China to low-income countries also increased, by a factor of 20. If China is included in the group of low- and middle-income countries, trade activities within this group will show an increase by a factor of 13 between 1990 and 2010. Trade to, from and within high-income countries, on the other hand, only increased by a factor of 2-4.

The trade activities of low-income countries (excl. China) mainly comprise imports and exports of mineral raw materials (i.e. industrial and metal minerals, as well as fossil fuels). In 1990, these goods made up 50-80 per cent of all traded goods (measured in tons). In 2010, the share was still between 60 and 85 per cent, the latter representing goods traded from low-income countries to China.

Trade balances in monetary and physical terms – providers and demanders

Net trade flows are obtained by balancing imports and exports, which classifies countries as either physically net-importing or net-exporting. Physically net-importing countries are dependent on materials in the form of goods from other countries for use in production processes or for final consumption. Physical net exporters, on the other hand, provide materials to global markets. In physical trade balances of country aggregates (such as the regions discussed in the following section), intra-regional trade balances out. Thus, the physical trade balance represents only inter-regional trade.

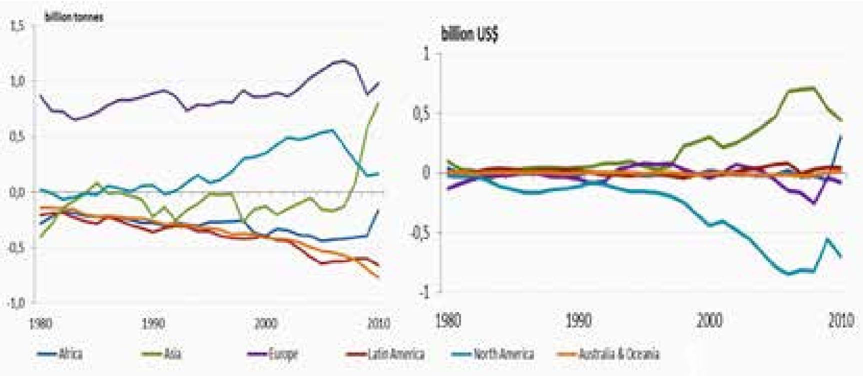
Until 2007, Europe was the biggest net-importer of commodities, followed by North America. The demand for commodities from Europe and North America was met by Latin America, Australia (including Oceania) and Africa (Figure 8, left).[10] Despite its high amounts of imports and exports, Asia's trade was physically well balanced until 2007. Thereafter, Asia's material imports increased much faster than its exports, resulting in a steep increase in its net imports. By 2010, Asia demanded nearly as many materials from the world market as Europe.

The dynamics of monetary trade balances are quite different. For economic reasons, monetary trade is usually more or less balanced. However, trade deficits and trade surpluses are not uncommon. Compared with recent years, monetary trade balances were more or less even throughout regions during the 1980s. From 1990 onwards, Asia – the second largest importer of materials – increased its trade surplus steadily. In the case of North America, imports steadily exceeded exports, and so North America has had by far the most deficient monetary trade balance since 1980; its monetary trade balance nearly inversely mirrors Asia's monetary trade balance (Figure 8, right). The other regions had a much more even trade balance until recently. Since the 2008 economic crisis, however, patterns appear to have changed, especially for Africa, which has experienced a steep increase in its trade surplus.

10 It should be noted that in particular some African countries are still missing in the assessment of 2010, thus here and in the following figures, the African values for 2010 should be taken as preliminary.

Figure 8

Trade balance by continents in physical (left) and monetary (right) terms, 1980–2010

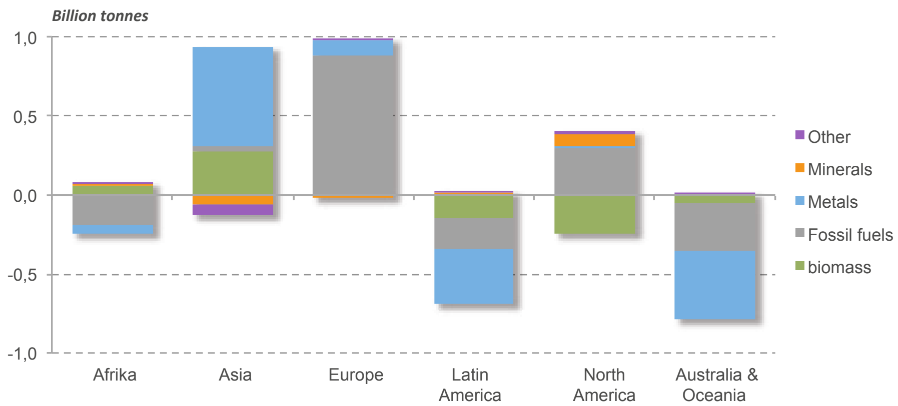


Sources: physical terms:(Dittrich, 2012), monetary terms: (UN, n.d.); please note: while monetary trade balances are counted as exports minus imports, physical trade balances are counted as imports minus exports.

Fossil fuels also dominate trade balances. African countries have supplied mainly fossil fuels and metals to the world market, while increasingly importing biomass, specifically cereals. Asian countries, and in particular West Asian countries, have been the largest suppliers of fossil fuels for many years. At the same time, East and South Asian countries have increasingly imported fossil fuels. In 2010, the large net import of fossil fuels was matched by the large fossil fuel net exports of Western Asia, resulting in a near balance of fossil fuels for the Asian continent (Figure 9). Asian countries need increasing amounts of biomass and metal materials, and were consequently the largest net importer of both material categories in 2010. Europe imported and exported commodities from all material categories, and thus its net trade is fairly balanced. Fossil fuels are the only category with mainly positive physical trade, with Europe importing large amounts of fossil fuels for domestic final use. Australia (including Oceania) exported all kinds of materials, in particular metals. In 2010, it was the largest net supplier of metals and fossil fuels of all the continents. North America, being the largest exporter of biomass, has increased its exports of biomass only slightly over the decades. It is followed by Latin America, which was also the second largest net exporter of metals and fossil fuels in 2010.

Figure 9

Physical trade balances of continents by material category, 2010



The Physical Trade Balance (defined as imports minus exports) of a region represents only inter-regional trade; intra-regional trade balances out.

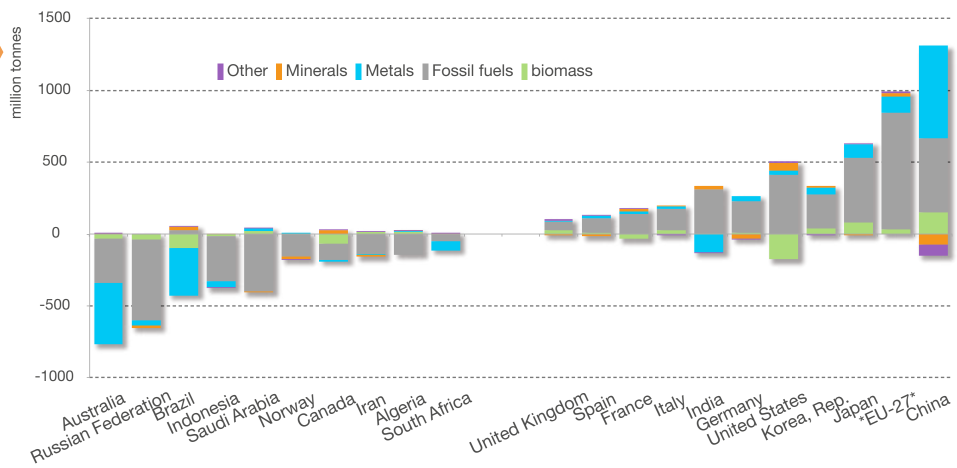
Source: (Dittrich, 2012)

Trade, in physical terms, has been dominated by a minority of countries, although concentration in trade decreased in the period from 1980 to 2010. In 1980, the ten countries with the highest trade volume imported and exported together 56 per cent of all traded materials, while the ten largest trading countries imported and exported 46 per cent of globally traded materials in 2008. In contrast, the 75 countries with the lowest trade volumes increased their share only slightly; together they imported and exported 0.6 per cent of globally traded materials in 1980 and 0.8 per cent in 2008. The global financial crisis again led to a higher concentration in trade, combined with a larger participation by small trading countries: the ten largest trading countries were responsible for 50 per cent of physical trade volumes in 2010, and the 75 countries with the smallest physical trade volume traded 1.2 per cent of materials.

The countries that dominate trade in physical terms show different trade profiles with respect to imported and exported materials. In 2010, Australia was the largest exporter of materials with a diverse export structure including commodities made up of biomass, metals and fossil fuels (Figure 10). Australia was followed by the Russian Federation, which exported mainly fossil fuels. Brazil's export structure is not as diverse as that of Australia, but still covers a wide range of metals and biomass, while Indonesia's exports were mainly dominated by fossil fuels. China imported the most materials in 2010, mainly metals, followed by fossil fuels and biomass. The second largest importer was the EU-27, where imports were dominated by fossil fuels. Although the United States imports more non-renewable materials than the Republic of Korea, it has fewer net imports, owing to its exports of biomass. It is interesting to note that, apart from China, the imports of other large net importers are dominated by fossil fuels. Metals hold the second-largest import share, except in the case of India, the third largest supplier of iron and steel.

Figure 10

Largest net exporters and importers by material composition, 2010



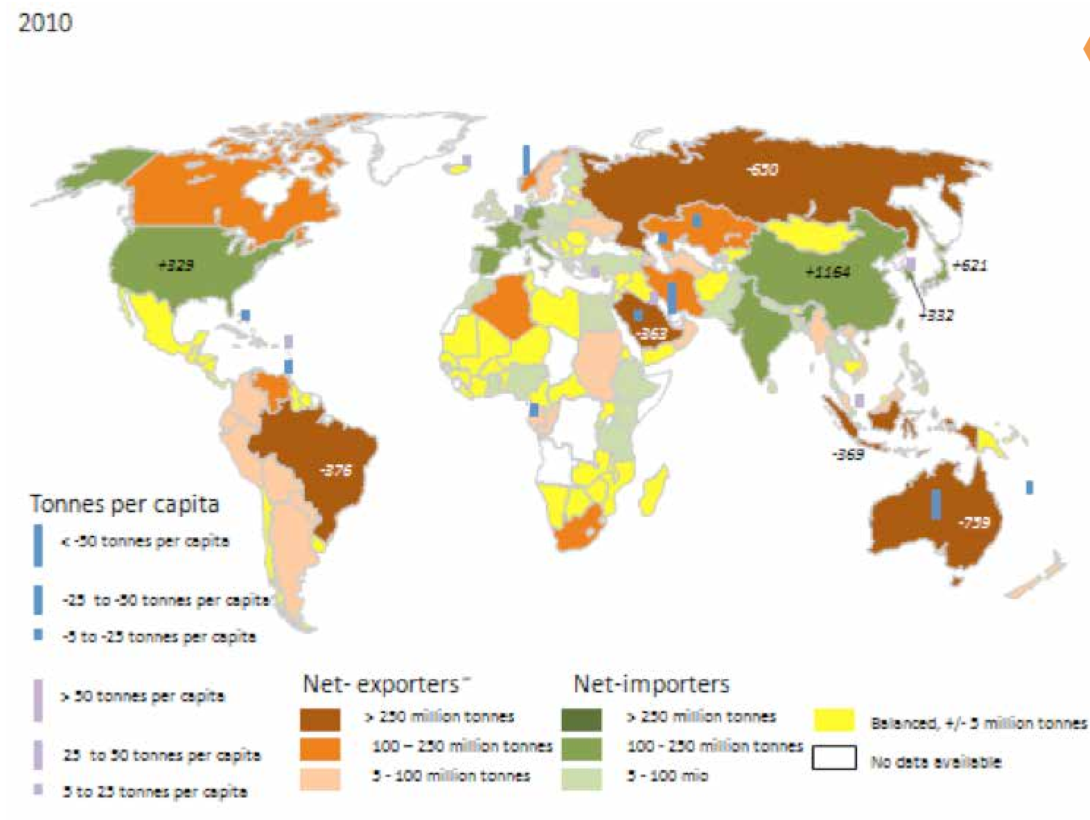
Source: *(Dittrich,* 2012)

The number of net importing countries exceeded the number of net exporting countries in all years, and increased over the years. In 2010, 30 per cent of all countries supplied materials to world markets, while 70 per cent of all countries net-imported them. In 2010, South American countries, Canada, Scandinavia, west and central Asian countries, as well as Australia and the south-eastern Asian islands, were the largest suppliers of materials. The United States, Japan and west European countries remained large importers throughout the three decades. While the number of net exporters is decreasing, they are increasing their export volumes in order to meet growing demand from the world market.

2. Trade in resources and commodities

Figure 11

Physical trade balances of countries, 2010



Source: (Dittrich, 2012)

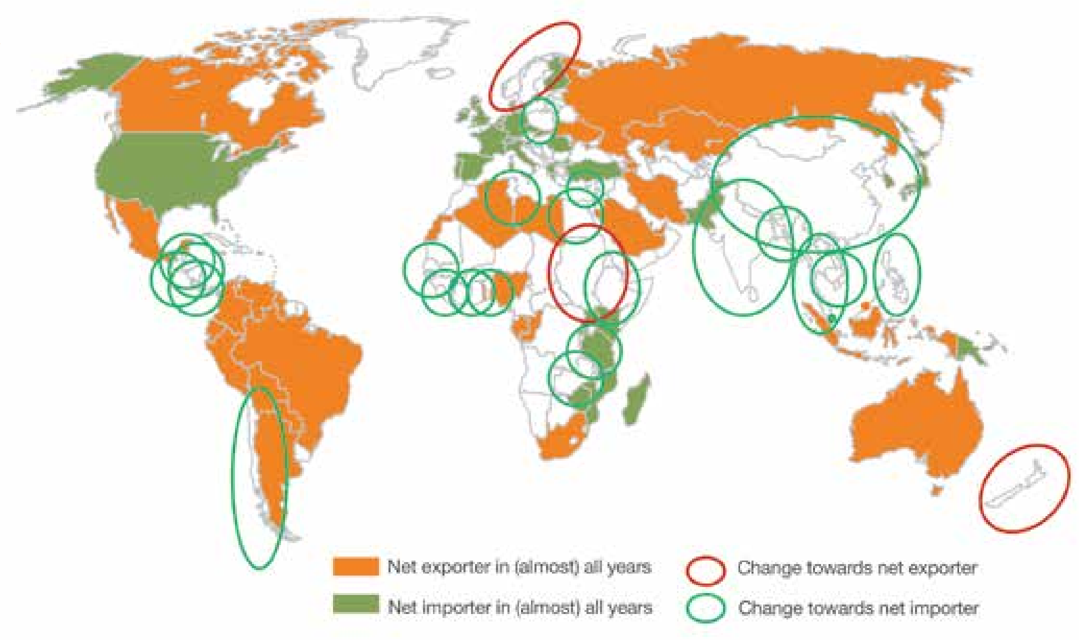
At the same time, countries generally have not changed their overall pattern of being a net importer or net exporter over the years. Western European countries, Japan and the United States but also several poor countries, in particular in south-east Africa (e.g. Madagascar and Uganda) have remained net importers of materials all along. South America, Central Asia, the Middle East and Australia, on the other hand, are providing resources and often figure as what Eduardo Galeano (1997) described as the "Open Veins" (of Latin America). Only a few countries have changed from being net exporters to net importers (for example, countries in south-east and south-west Africa). China and India, as the most populous economies in the world, are among these countries. Figure 12 highlights countries that have been persistent suppliers or importers of resources and countries that have changed their patterns.

The pattern change from being a resource importer to becoming a supplier accompanies the discovery of resources, in particular oil. Sudan is an example of this process. Since the extraction of petroleum started in 1996, Sudan has increasingly exported it, outbalancing previous imports. Countries that shift from exporting resources to importing them are often rapidly emerging economies, where an increasing demand for imports (mainly for fossil fuels but also for other goods) is outpacing the equally increasing amount of exports.[11] India is an example of such a trend: since the 1990s, increasing imports of fossil fuels have exceeded its (also increasing) exports of iron ores. In countries with a rising population, such as Kenya or Egypt, increasing demand for food and energy exceeds the countries' increasing exports of predominantly agricultural produce.

11 Even if these emerging economies use their imports to produce commodities which are not for internal/domestic? [Nina: yes, domestic] demand, they shift to a positive physical trade balance, as the raw materials imported have more weight than the goods they produce from these raw materials for exports. This applies particularly to energy carriers used in the production process.

Figure 12

Persistence and change in net-importing and net-exporting countries, 1962–2010



Source: (Dittrich, 2012)

Increasing dependency on the world market

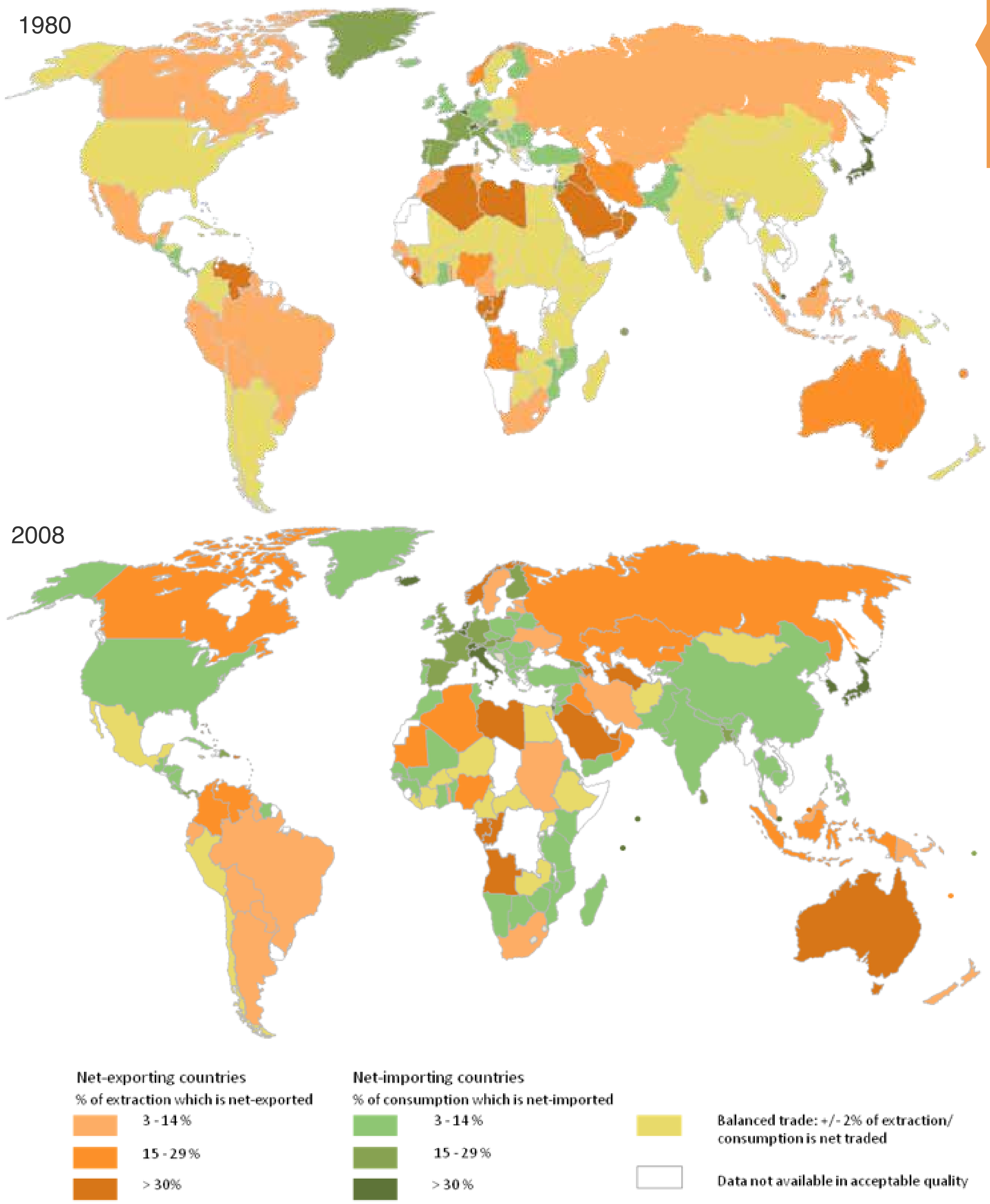
The higher the share of imports in a country's total annual input of materials (DMI = direct material input), the higher its dependency on the world market. In countries with little integration into the world market, import dependency is low. This applies, for example, to Sudan, Burundi, Central African Republic, Iran, Ethiopia and Afghanistan: their share of imports in DMI is less than 2 per cent. In contrast, small high-income countries, such as the Netherlands, Singapore and Belgium-Luxembourg, are highly integrated with the world market and hence show the highest dependencies; they need to import around three-quarters of their materials input (data for 2008).

Global dependence on material imports has increased during the past three decades, because the imports of most countries have increased faster than their extraction rates. Whereas, in 1980, only 27 per cent of all countries net-imported more than 3 per cent of their material input (DMI), in 2008, 51 per cent of all countries did so (see Figure 13). At the same time, there was not a significant rise in the number of net-exporting countries (which net-exported more than 3 per cent). Thus, while in 1980 there were 54 import-dependent countries, as opposed to 36 countries with high net exports, the ratio changed to 102 versus 45 by 2008.

Dependence on the global market for delivering vital commodities is increasing substantially around the world. All material categories witnessed an increase in import dependency, but the most significant rise was seen in resources such as fossil fuels and metals. In 2008, more than 100 countries imported more than half of their fossil fuel requirements (85 countries in 1980) and 97 countries imported more than half of their metals requirements (75 countries in 1980). Fossil fuels and metals are special cases in terms of dependence: in 2008, 24 countries exported more than half of their fossil fuel extraction (20 countries in 1980) and six countries exported more than half of their metal extraction (10 countries in 1980). But import dependence is not limited to these point resources (metals and fossil fuels) that are not available everywhere in the world. For countries with unfavourable bio-geographical conditions, for example small islands such as the Seychelles, or West Asian countries such as Kuwait, biomass imports are vital and supply more than half of the biomass these countries need (9 countries in 1980). At the same time, only a few countries are net providers of a large share of their biomass: no country exports more than half the biomass it extracts.

Figure 13

Geographical distribution of resource dependence in 1980 and 2008



Source: (Dittrich *et al.*, 2012)

Thus, global interdependency is rising, but the vulnerability of the current trading system is also increasing: its balance relies on ever fewer resource producers. If some resource producers experience depletion of their sources or decrease or even stop exports for political/military reasons, this may have a major destabilizing impact on countries depending on those imports.

2.3 Is the organization of the world market still scaling with income levels, or are new patterns emerging?

Throughout most of the 20th century, global trade patterns tracked income patterns. High-income industrial countries imported a large amount of resources, mainly from low-income countries, and exported a smaller amount of processed goods to the low-income countries. Up until the 1980s, only high-income OECD countries were net importers of materials, while all other countries were net suppliers. During this period, resource prices consistently declined (see also Dobbs *et al.* 2013). These patterns are, according to the analysis of Raul Prebisch (1949), characterized by the use of natural resources and unqualified labour, whereas the imported products from the North are capital- and knowledge-intensive. In Prebisch's interpretation of the international "division of labour" between the centres and the periphery, a centre can acquire the primary material and energy resources for its production and consumption from the periphery at a continuously declining price, while economic development at the periphery is hampered by rising prices for the imported goods it requires. Prebisch suggested that a development strategy will not be successful if economic activity in the south is concentrated on the production and export of primary commodities to industrial centres (Pérez-Rincón, 2006, p. 520; Prebisch, 1949; Singer, 1950). The deterioration of the terms of trade for the South is theoretically explained by two complementary economic hypotheses: (1) the hypothesis of low income-elasticity of demand for raw materials, and (2) hypothetical asymmetries in the labour market. In the case of manufactured goods, the fruits of technical progress and increased productivity benefit both entrepreneurs and workers, through higher profits and wages, whereas, for primary products, technical progress translates into lower prices and lower wages (see also Singer, 1950). This decline is rooted in relative labour surpluses in developing countries, which have greater difficulty in employing labour displaced from subsistence work in other sectors. Southern countries were typically in close exchange relations with the rich North and thus trapped in a "development of underdevelopment" (Frank, 1966).

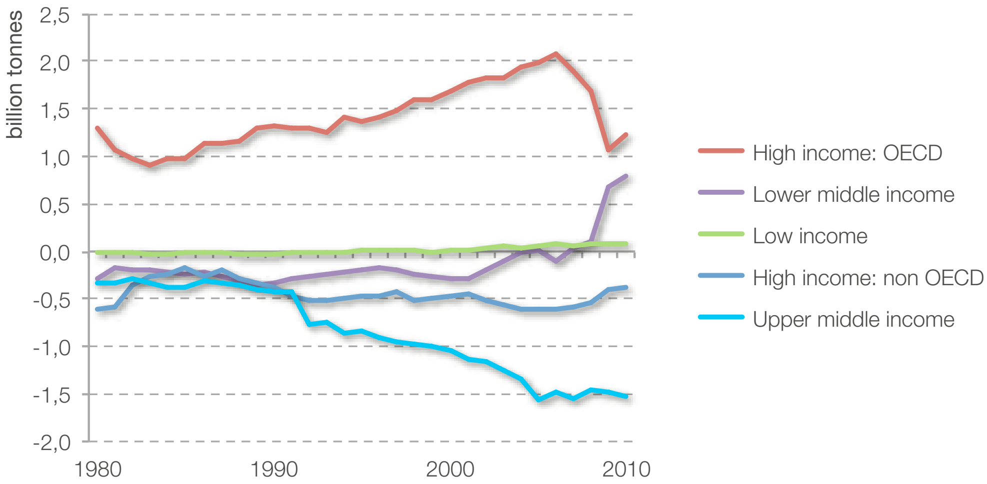
Since the turn of the century, these patterns of "unequal exchange" appear to have undergone significant change. During the twentieth century, rapidly growing resource use coincided with decreasing prices. Since 2000, the global demand for resources has risen faster, driven, in particular, by rapidly emerging economies such as China. The increasing competition for resources and the rising prominence of scarcity of natural resources as issues of strategic importance leads to gains in political and economic power for resource-rich countries. These gains are realized as a result of the increased value of extraction and exports, hence impacts on the world economy, power structures and trade are to be expected.

In recent decades, non-OECD countries with high incomes (mainly oil-exporting countries), countries with upper-middle incomes, such as Russia, Brazil and South Africa, and also high-income OECD countries, such as Australia, Canada and New Zealand, have become important suppliers of materials to the world market. At the same time, countries with lower-middle incomes have increased their net imports substantially, steadily changing their profiles from suppliers to importers. The most spectacular example of this trend is China.

This trend might be a potential structural change, where income is gradually overtaken by other factors such as population density – a variable identified by Krausmann *et al.* (2008) – in explaining world trade patterns. Densely populated countries increasingly appear as net importers on world markets, while sparsely populated countries supply materials, irrespective of their income levels (Figure 15). The material volumes reallocated from low population density to high population density countries tripled between 1980 and 2008.

Figure 14

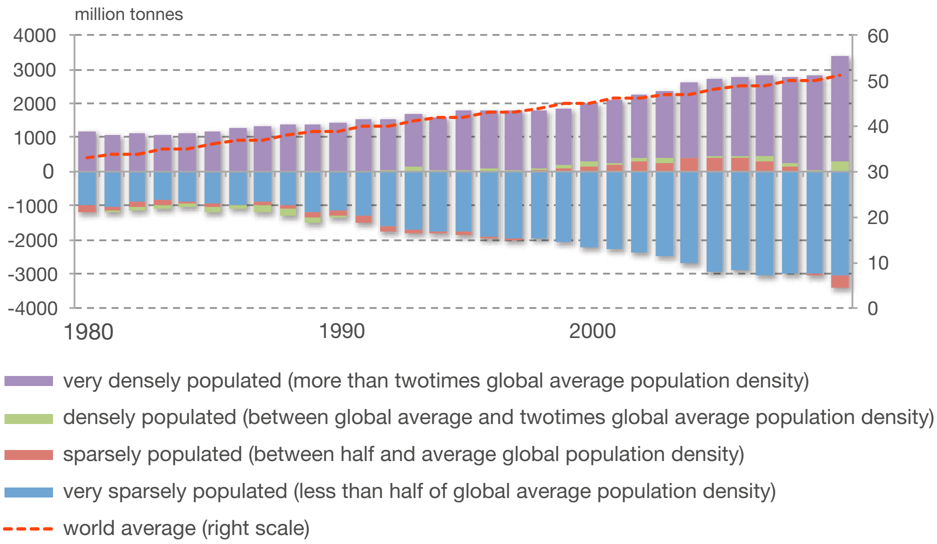
Countries' physical trade balances by income group, 1980–2010



Source: (Dittrich, 2012); Assignation according to World Bank (2012).

Figure 15

Physical trade balances by country group according to population density



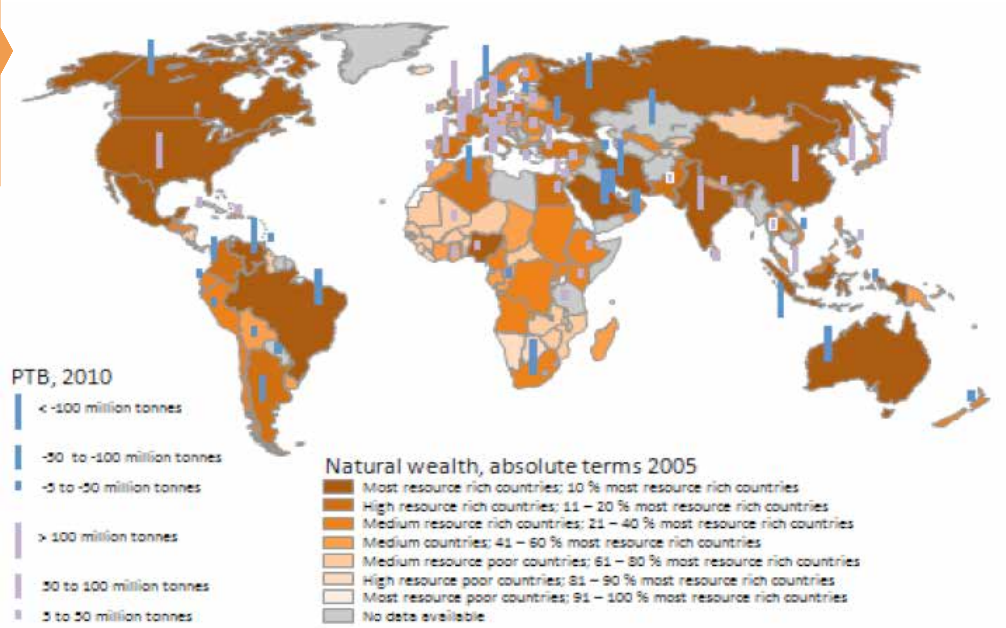
Sources: (Dittrich, 2012; World Bank, 2012)

Resource endowment (as measured by the World Bank) [12] is another important determinant of physical trade patterns, as it has a high correlation to physical trade balances. For the past three decades, consistently 10 per cent of the resource-rich countries (which in absolute numbers comprises 15 countries) have been net suppliers of materials to global markets (Figure 16). There are a few remarkable exceptions. Some of the most resource-rich countries, such as China, the US and India, were net importers, and some rather resource-poor countries, like Guyana or Latvia, were net exporters of materials. Finally, other factors such as technological development and newfound access to resources also influence extraction and trade patterns. The exploitation of shale gas is an example of this.

12 The Resource Endowment initiative was set up by the International Council on Mining & Metals (ICMM), UNCTAD and The World Bank, with the aim of better understanding the impact of mining activities on the socio-economic development of resource-rich but low- and middle-income countries.
Source: ICMM (2006): Resource Endowment initiative. Analytical Framework. Summary, www.icmm.com (http://www.icmm.com/page/2905/resource-endowment-initiative-analytical-framework-summary

Figure 16

Natural wealth (2005) and physical trade balances (2010), absolute terms



Sources: (Dittrich, 2012; World Bank, 2012)

Infobox 2

Labour time embodied in trade

The use of environmentally extended models has led to the recognition of the upstream labour required for traded products in the form of a 'labour footprint', as a significant theme. Human resources invested in labour can also be considered a natural resource. On the basis of the Eora MRIO Database, Alsamawi and colleagues (2014) have worked to establish both the employment and the wage footprint of nations, calculating the working hours (standardized to full-time employment equivalents) and the associated wages embodied in global imports and exports.

There are large differences between countries (and country groups, see Fig. X) with respect to the share of the domestic workforce engaged in exports production. In western industrial, Middle Eastern and Northern African (MENA), and Latin American countries (LACA), about 15 per cent of the workforce is engaged in exports production, whereas Asian and (ex)USSR countries employ 20-30 per cent of the domestic workforce in the same sector. In Sub-Saharan Africa, this share rises to 40 per cent in some cases. Foreign labour engaged in production for domestic consumption, however, follows a converse pattern: western industrial countries are sustained by 47 per cent foreign labour, while in Asian countries the figure is only 5 per cent.

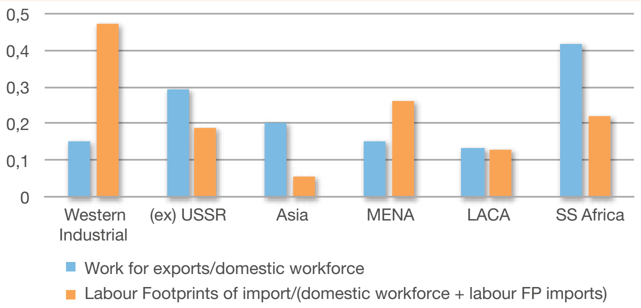
This is explained by wage levels. Alsamawi *et al.* (2014, p. 64) illustrate the point:

"French people (average domestic wage US$ 50,000) smoke cigars that are manufactured in Poland (average domestic wage US$ 10,000), which, in turn, relies on raw material that is produced in Tanzania (average domestic wage US$ 170). Tanzania itself imports computers that are produced in China and designed in the United States. However, the volume of goods and the amount of labour embodied in those imported goods is not equivalent to the amount of exported labour and volume of exported goods. In 2010, approximately 500,000 labourers in Tanzania worked to support US consumption (earning US$215 million), whereas approximately 3,000 labourers in the United States worked for Tanzania (earning US$ 50 million). As an example of longer chains, U.S. citizens (average domestic wage US$ 58,000) wear clothes that are manufactured in China (average domestic wage US$ 2,700), woven from yarn in Pakistan (average domestic wage US$ 1,460) made with raw cotton from Tajikistan (average domestic wage US$ 450). The manufacture of a car in Germany may need the following:

2. Trade in resources and commodities

copper from Chile (average domestic wage US$ 12,330) and Zambia (average domestic wage US$ 1,600); natural rubber or tyres from Indonesia (average domestic wage US$ 2,200); iron and aluminium from Brazil (average domestic wage US$ 10,170). … Each country makes use of a yet poorer one to deliver the imports needed to produce their exports."

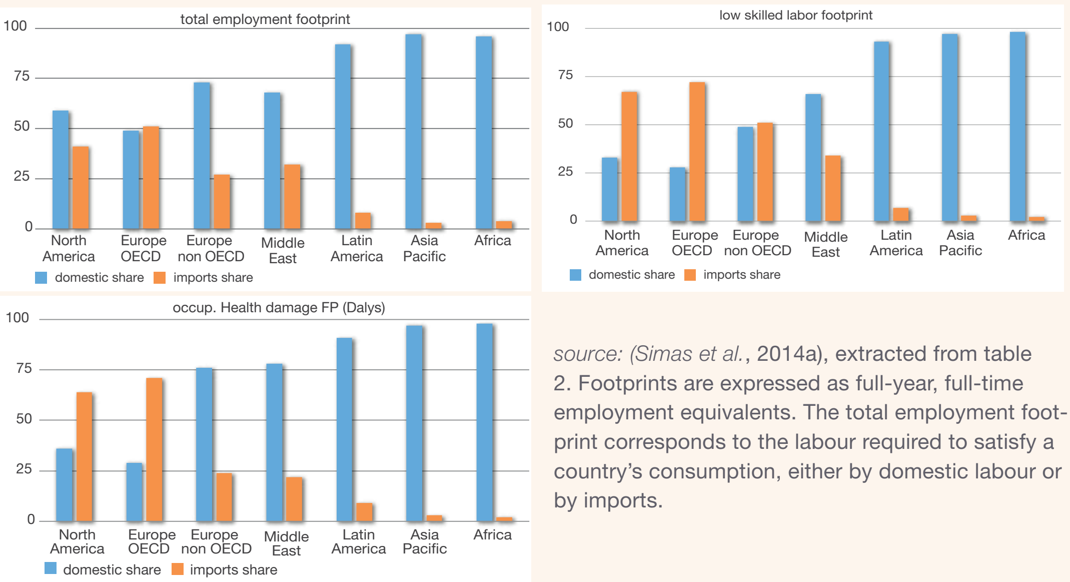
Figure 2.1 Labour embodied in countries' exports relative to their domestic workforce, and labour embodied in imports relative to the labour required for all domestic consumption (2008)



Source: calculated from data from Alsamawi *et al.* (2014). Their data were generated on the basis of the EORA model (Lenzen *et al.*, 2013) with labour time data from LABORSTA (ILO, 2014). Accounting unit: full-time employment equivalents (employed and self-employed). Ordered by country group according to Schaffartzik *et al.* (2014b).

M. Simas and colleagues take a similar approach to calculating labour embodied in trade, generating indicators for labour and energy productivity that are dependent on a 'territory-based' and 'consumption-based' calculation and exploring their implications for greenhouse gas emissions (Simas *et al.*, 2014b). They also link domestic consumption to the exports and imports of what they term 'bad labour'. Indicators for bad labour include labour resulting in occupational health damage (accounted for in disability-adjusted life years (DALY)), vulnerable employment (employment without formal employment bonds), an under-representation of women in the workforce, a high proportion of low-skilled workers, child labour and forced labour. By using EXIOBASE, an extended MRIO model, Tukker *et al.* demonstrate that North America and OECD-Europe employ about as much foreign labour as domestic labour to satisfy domestic consumption, while all other world regions import much smaller shares or hardly any foreign labour (Tukker *et al.*, 2014).

Figure 2.2 Employment footprint and selected 'bad labour' footprints by world region (2010)



source: (Simas *et al.*, 2014a), extracted from table 2. Footprints are expressed as full-year, full-time employment equivalents. The total employment footprint corresponds to the labour required to satisfy a country's consumption, either by domestic labour or by imports.

Labour footprints of 'bad labour' are even more skewed: North America and OECD Europe import more low-skilled labour for health-damaging work than they employ domestically, while all other world regions tend to employ domestic low-skilled labour for hazardous work, but import highly skilled labour for less hazardous work. In this way, global inequalities are also reflected in international trade.

Credit: Hans Splinter, flickr

3. Upstream resource requirements of traded commodities

Sustained availability of natural resources is essential to overall human wellbeing. In a scenario of increasing demand for resources and, at the same time, accelerated depletion of those very resources, trade can contribute to supporting resource efficiency on a global scale. In principle, international trade allows an efficient allocation of production and extraction activities to regions with a large availability of resources and minimal resource intensity; this facilitates a reduction in economic costs, but possibly in environmental and social costs, too.

Foreign trade statistics only consider the mass or material flows of the goods at the time of crossing state borders. However, there are additional materials used in the upstream production process that remain at production locations as wastes and emissions. These additional materials, termed "upstream material requirements", are extracted or harvested from the natural environment and used in production, but are not physically transferred to the importing country and hence no longer contribute to the weight of the goods. [13] Upstream material requirements are also known as 'materials embodied in trade', 'indirect flows', 'hidden flows', 'virtual flows' or 'ecological rucksacks'. Indicators for upstream resource requirements are expected to capture resource use along the production chain and allocate environmental burden to the place of consumption. Beyond directly traded masses, upstream flows provide insights into the overall physical dimension of trade.

The sum of materials traded and the associated upstream material requirements is calculated under the term Raw Material Equivalents (RME) (Eurostat, 2013, 2009, 2001; OECD, 2008).

In the Introduction, we explained how a product gets lighter in weight but becomes more valuable in its progress along the extraction-consumption chain. A country engaged in exports experiences a steady depletion of its natural resources to provide resources to global markets. In doing so, the exporting country has to deal with wastes and emissions from primary processing, and may not be gaining high economic revenue. With regard to this particular resource and the goods derived from it, consumption-based indicators (such as RMC) will mark this country as having a light material footprint (MF): its inhabitants have low levels of resource consumption. Production-based indicators, on the other hand, (such as

13 See Introduction for an explanation of how a product becomes lighter in weight but more valuable during its progress along the extraction-consumption chain.

Domestic Material Consumption (DMC)) will mark this country as high in resource use, creating a substantial environmental burden within its territory. Both markers have their justification. Indicators of direct material consumption (like DMC) attribute resource use in production and consumption processes to countries by what happens on their territory and under their direct governance.

In the existing literature, upstream resource requirements have been compiled for energy, water, land and materials. These compilations follow their own terminological and methodological traditions. Energy requirements can be expressed either as energy resources used (in primary energy) or as CO2 emissions caused by the use of (fossil) energy resources. Studies calculating upstream CO2 emissions are quite advanced (Baiocchi and Minx, 2010; Caldeira and Davis, 2011; Davis *et al.*, 2011; Hertwich and Peters, 2009; Peters *et al.*, 2011; Wiedmann and Barrett, 2013). For upstream water requirements, the term 'virtual water accounts' is commonly used (Hoekstra, 2003). Upstream land requirements have been addressed as "global hectares" in the footprinting tradition (Rees and Wackernagel, 1994) as well as – indirectly – by accounting for Human Appropriation of Net Primary Production (HANPP; Haberl *et al.*, 2007). Approaches accounting for upstream material requirements have been the subject of intensive research efforts in the past decade. However, the findings from these studies are not conclusive; they are based on different methods or combinations thereof, built upon different system definitions and time frames. Consequently, results cannot easily be compared. In the sections below, we attempt to give an overview of the existing literature.

There are two main approaches used in the estimation of upstream resource use associated with trade: an input-output approach through the use of MRIO models on a global scale, and an LCA-approach using coefficients from the life cycle inventories of products.[14] These two approaches are combined to form "hybrid" LCA-IO approaches (for details see Section 1, Infobox 1). The methods produce rather different results, which we report on in the following two subchapters.

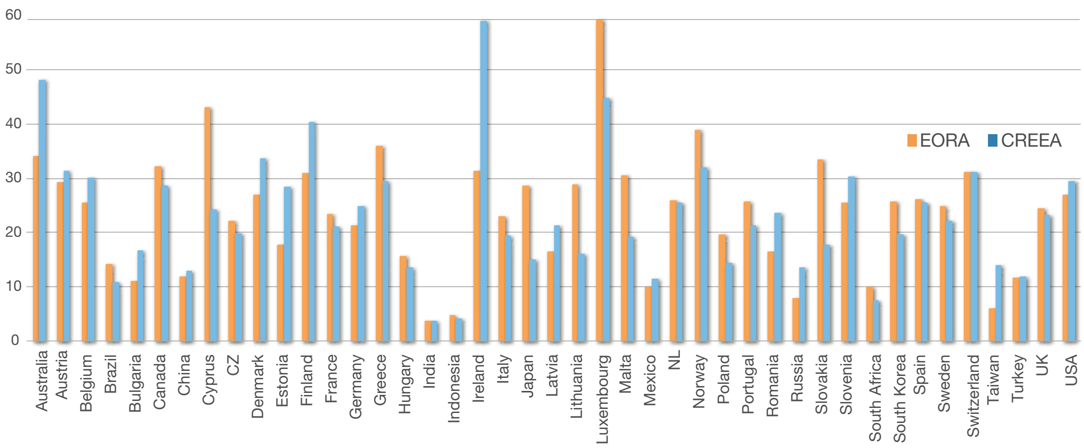
14 For further information and a description of methods, see the section on "Material Flow Accounts – methods and data" in the introduction to this report.

3.1 Upstream material requirements of international trade: findings from studies using an environmentally extended Multi-Regional Input-Output approach (MRIO)

In 2013, Wiedmann *et al.* (2013) published the first results of a global, comprehensive study on upstream material requirements, using Eora – a highly disaggregated and complex MRIO model (www.worldmrio.com) –, which includes 186 countries and covers the period 1990 to 2008. Wiedmann *et al.* (2013) revealed that 40 per cent of all globally extracted materials are associated with trade activities and final demand in countries other than the country of extraction. Concerning industrialized countries, the study found upstream requirements of net imports to be significantly higher than net direct trade, implying an 'outsourcing' of material use through trade. The difference is much smaller for emerging economies. The trend is the reverse for resource-extracting economies, since significant amounts of extraction are associated with final demand in other countries. A study published by Tukker *et al.* (2014) uses EXIOBASE, another multi-regional Input-Output model, to yield material footprint accounts (as well as footprints for other resources such as carbon, water and land) for 48 countries. The two studies present similar results for 42 of the 48 countries studied by Tukker *et al.* (2014) (see Figure 18). However, for Cyprus, Ireland, Japan, Lithuania, Malta, Slovakia and Taiwan, respectively, there is a more than 50 per cent material footprint difference.

Figure 17

A comparison of material footprint results from Eora and CREEA



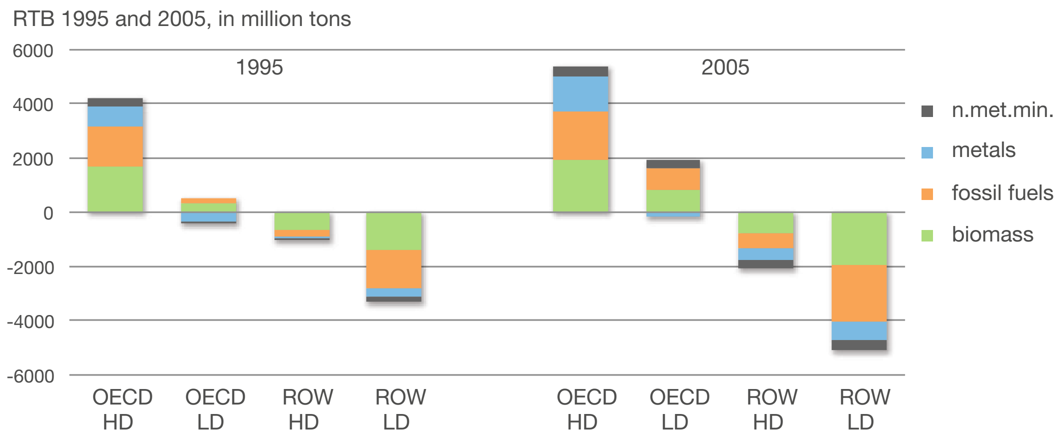
Sources: CREEA: Tukker *et al.* (2014); Eora: Wiedmann *et al.* (2013)

These discrepancies illustrate that there is still a need for methodological harmonization with regard to the calculation of upstream materials of trade. Rapid improvements are happening, and there is close collaboration between the various research teams, so that, in the near future, research results can be expected to gain in reliability.

In a 2012 study by Bruckner *et al.* (2012), comparing the trade balances of OECD and non-OECD countries, OECD countries were shown to be net importers on RME criteria, while non-OECD countries were net exporters. This contrast between the two sets of countries is more pronounced when trade balances are measured in terms of raw material equivalents rather than direct trade. The study shows that the contrast increased between 1995 and 2005. Population density exerts a significant influence on raw material trade balances (RTBs), with populous OECD countries emerging as large consumers of raw materials and less populous countries from the rest-of-the-world (ROW) region supplying the largest share of raw materials to match global demand.

Figure 18

Raw material trade balances between OECD countries and the rest of the world in 1995 and 2005, by population density



Legend: HD = high population density; LD = low population density
Source: (Bruckner *et al.*, 2012)

A similar study was done by Wiebe *et al.* (2012) for emerging economies between 1995 and 2005. This study showed that emerging economies as well acquired increasingly negative trade balances. A negative trade balance in materials usually means net exports of natural resources.

3.2 Upstream material requirements: findings from national studies using hybrid IO approaches or Single-Region IO approaches

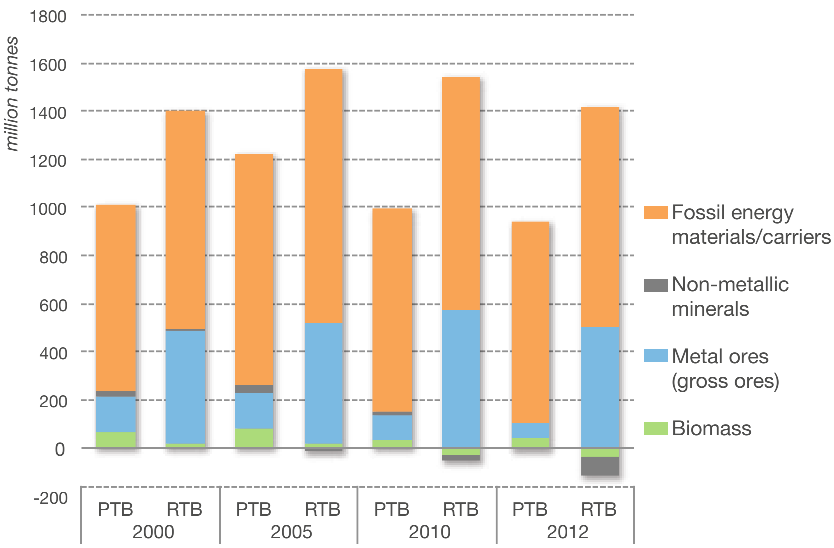
Schoer and colleagues (2012) have conducted a study of the raw material consumption and trade balances of the European Union.15 The study adopted a hybrid IO-LCA approach, calculating upstream material requirements using the monetary Input-Output table of the EU. The approach also integrated coefficients derived from LCA or other product-oriented coefficients, especially for metallic products and fossil fuels. Like those of Wiedmann *et al.* (2013), the results demonstrated that, for the EU27, raw material trade balances are significantly more positive (more imports than exports) than physical trade balances based on direct trade flows.

15 Eurostat, the European Statistical Office, commissioned the study. Results for the EU27 are available in time series, covering the period between 2000 and 2012, on the Eurostat website (Eurostat 2014).

Results are available for specific categories, too. EU27 trade in biomass and non-metallic minerals is more or less balanced, implying that net imports from other countries or regions are not required to support European production and consumption. On the other hand, EU27 countries require net imports of fossil fuels and metals; metals draw on large amounts of upstream material requirements. This is particularly true for metals like gold, iron and steel, and copper. The study showed that net imports of upstream material requirements increased between 2000 and 2005 and then declined between 2010 and 2012, presumably as a consequence of the 2009 economic crisis.

Figure 19

EU27 physical trade balance (PTB) and raw material trade balance (RTB)



Source: (Eurostat, 2014)

The hybrid approach to calculating the raw material equivalents of trade was also applied to three country-specific case studies. A study on Germany[16] (Buyny *et al.*, 2009; Buyny and Lauber, 2010) used a very detailed IO structure and incorporated a large number of product LCAs.

Studies on the Czech Republic (Kovanda and Weinzettel, 2013; Weinzettel and Kovanda, 2009) and Austria (Schaffartzik *et al.*, 2014a) were less detailed,[17] with LCA coefficients integrating mainly products of fossil fuel and metal goods. The

16 The German study strongly echoes the Eurostat methodology. It used a very detailed IO structure (120 sectors and 3000 products) and incorporated a large number of product LCAs (122) for those goods, which were not produced in Germany and hence no competitive production was given. The time series covers 2000–2007.

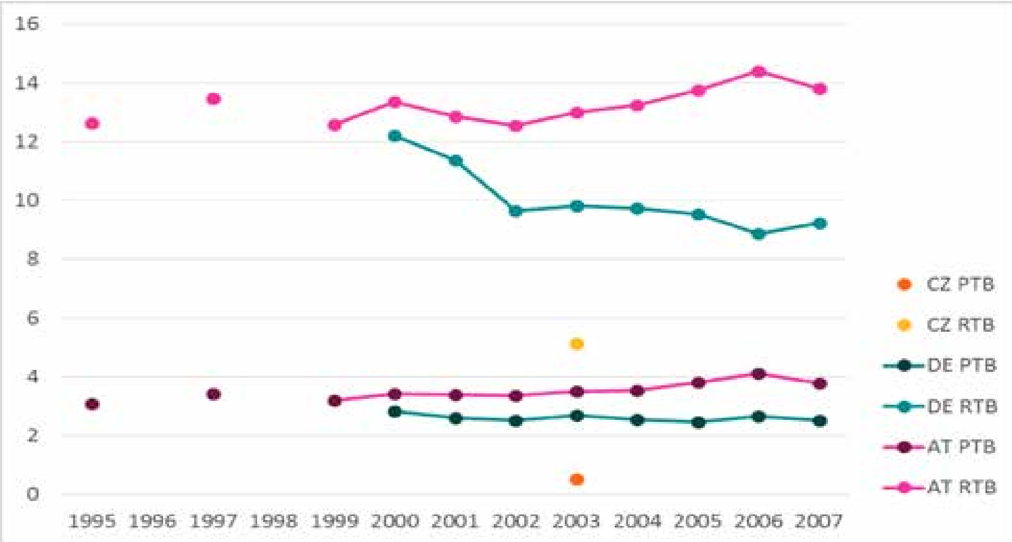
17 The studies on the Czech Republic (Weinzettel and Kovanda, 2009) and on Austria (Schaffartzik *et al.*, 2014a) cover IO tables of around 50 sectors or products and some 15 to 20 LCA coefficients used to calculate the RME of some fossil fuel and metal goods imports.

Czech study was conducted for 2003,[18] while the Austrian provides data for the years 1995 to 2007.

18 The calculation of RME for the Czech Republic is also available in time series (Kovanda and Weinzettel, 2013) and follows the trends of the Austrian RTB. However, detailed data were not available from the publication and so could not be included in this comparison.

Figure 20

Physical trade balances (PTB) and raw material trade balances (RTB) for Germany, the Czech Republic and Austria



Sources: Germany: Buyny *et al.* (2009) and Buyni and Lauber (2010); Czech Republic: Weinzettel and Kovanda (2009); Austria: Schaffartzik *et al.* (2014a)

Germany, the Czech Republic and Austria emerge as net importers in terms of direct trade flows (PTB), and this position becomes more pronounced for trade balances measured in raw material equivalents (RTB). For Austria and the Czech Republic, the disaggregated data along the four material sub-categories highlight the fact that the increase in net imports is mainly due to the high raw material equivalents of metal products. For Austria, fossil fuel-based goods contribute to a higher RTB. Across time, direct physical trade balances remain fairly stable, whereas the raw material trade balance for Austria and the Czech Republic indicates a slight rise (for a time series on the Czech Republic, see Kovanda and Weinzettel, 2013). The increase in RTB for Austria and the Czech Republic underlines the fact that these two countries are outsourcing material use associated with domestic final demand, at least to a certain extent. In contrast, the RTB for Germany is declining, implying that the country is requiring fewer foreign resources for domestic final consumption.

Shifting the focus to other world regions, in 2009 Muñoz *et al.* (2009) calculated the RMEs of several Latin American countries (Brazil, Chile, Colombia, Ecuador, Mexico) and the US for the year 2003, using a single-region IO approach[19]. The study showed Latin American countries to be net exporters of materials, both in terms of direct flows and upstream requirements. Low population density, favourable resource endowment and productive land support strong export specialization in Latin America.

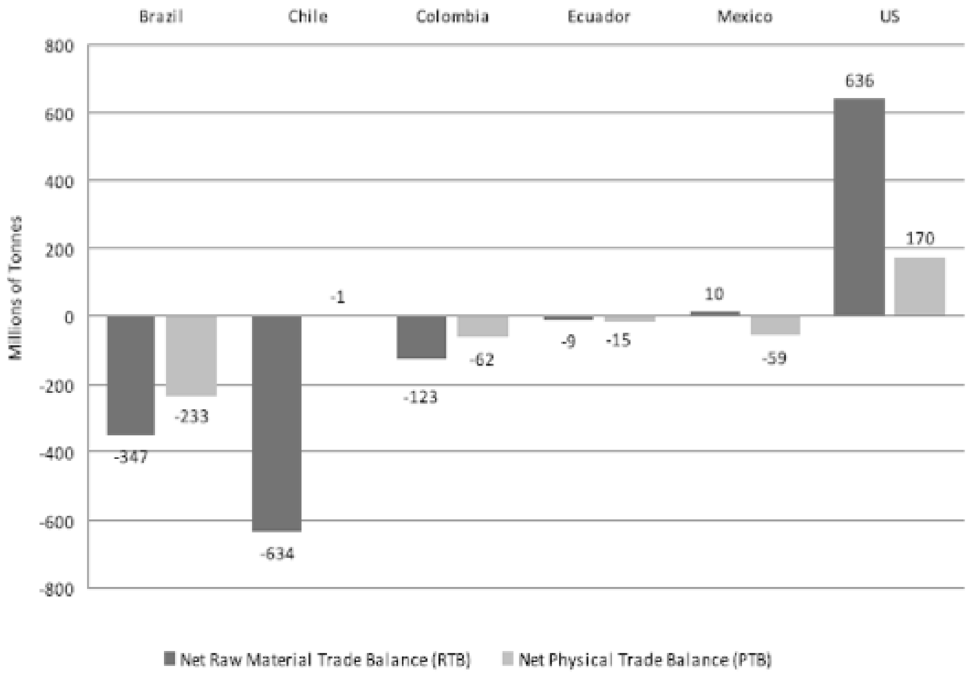
Increasing exports of biomass materials boosted net exports volumes significantly in Raw Material Equivalents terms (Figure 21) in the case of Colombia (by a factor of 2) and Brazil (by a factor of 1.5). Chile's raw material equivalents of its exports of copper increased its net exports by a factor of more than 600. This has to do with the fact that copper ore contains around 1 per cent of the metal only. For every ton of direct metal

19 In a single-region IO approach, RME of imports are calculated on the basis of domestic inter-industry relations and technical coefficients and thus assumes that the domestic production structure adequately represents, hence is applicable to, foreign production structures.

export, therefore, a large amount of waste rock is created, which inflates the upstream flows of these exports (for a discussion, see Giljum, 2008).

Figure 21

Raw material trade balances (RTB) and physical trade balances (PTB) for Latin American economies and the USA (2003) in million tonnes



Source: (Muñoz et al., 2009)

Fossil fuel exports contribute to an increase in net exports in RME terms in the case of Ecuador and Mexico, but raw material equivalents for imports have grown even more. For Ecuador, this results in a lower raw material trade balance compared with its direct trade balance, while Mexico's trade balance shifts from negative (i.e. net exporter) to positive (i.e. net importer).

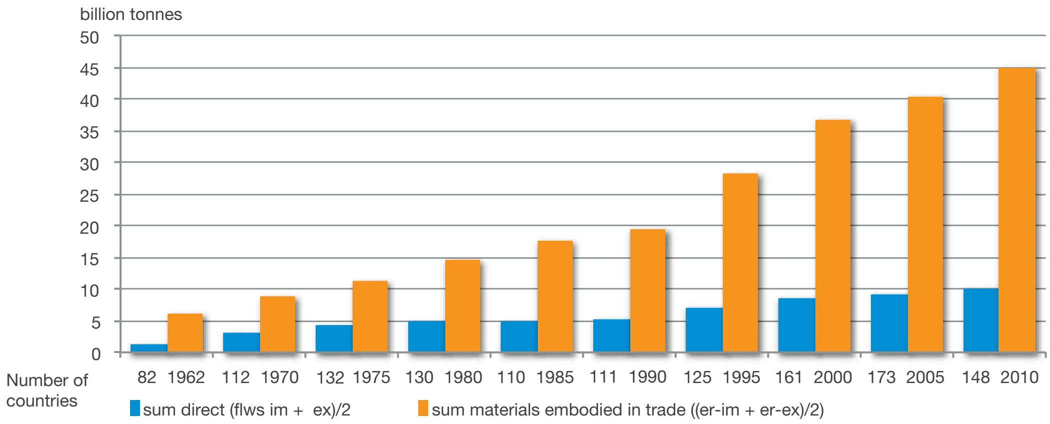
The United States of America is similar to Latin American countries with respect to high domestic material extraction, low population density, favourable resource endowment and a high share of primary production and heavy industry. However, the US is an industrialized economy with a much higher purchasing power for imports. Consequently, both its direct net imports and its imports including upstream materials are highly positive.

3.3 Upstream material requirements from a life cycle perspective

Dittrich *et al.* (2012) estimated that upstream requirements (including used and unused extraction) have increased faster than direct trade flows since 1962. In 2010, upstream (used and unused) material requirements were calculated to be around 44 billion tons. According to Krausmann *et al.* (2009), global material resource extraction in the same period was about 70 billion tons.

Direct trade and upstream material use associated with trade, 1962–2010

Figure 22



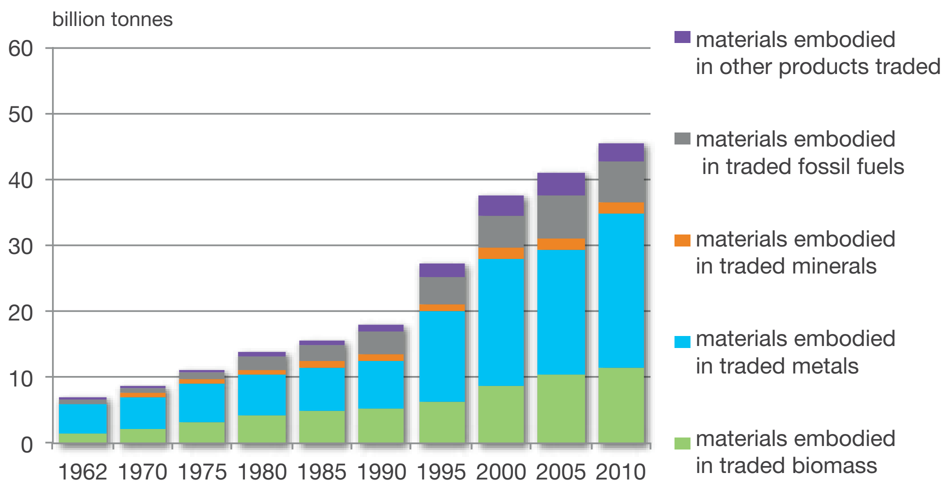
Sources: (Dittrich, 2010) for the years 1962–2005 and (Dittrich, 2012)for 2010; *countries included in the assessment of materials embodied in trade

The increase in upstream material use for traded goods was much higher than the growth of the traded goods themselves. On average, one kilogram of traded product carried an ecological rucksack of around 4.3 kilograms in 2005 and 2010, compared with 3.7 kilograms in 1980. This can be partly explained by the rapid growth in the trade of several commodities associated with high upstream flows, such as copper, hard coal, and biomass-based products likepaper and vegetable oils. In comparison, commodities with low upstream requirements, like petroleum, posted slower growth in trade.

Upstream material requirements of traded metals, in the form of ores, semi-manufactured or manufactured goods have accounted for around 50 per cent of the indirect flows of all traded goods since 1962. Fossil fuels, the dominant product group in terms of direct trade, are only responsible for around 15 per cent (2010) of all upstream material use, mainly relating to trade in hard coal (Figure 23). The resources with the highest shares of associated indirect flows in 2010 were iron (as ores, concentrates and steel), hard coal and copper. They were responsible for 13.5, 9.9 and 9.6 per cent, respectively, of all upstream flows associated with traded goods (see also Dittrich et al., 2012).

Upstream material requirements by material category of traded commodities

Figure 23



Sources: (Dittrich et al., 2012) for the years 1962–2005; (Dittrich, 2012) for the year 2010

Traded metal products embody the highest upstream requirements, followed by biomass products and fossil fuels. Non-metallic minerals do not carry significant upstream requirements, either in direct trade or in upstream material requirements. The high share for metal products is driven by the high amount of unused extraction and waste rock accumulated in metals processing as well as the high energy resulting from the use of fossil fuels in this processing. The share of upstream flows associated with fossil fuels is lower than among direct flows, because the extraction of fossil fuels does not encompass large waste flows like metals, and because fossil fuels are mostly used as an energy source that does not involve lengthy trade chains.

The trade balances of upstream material requirements differentiate between regions with high exports and those with high imports. Dittrich *et al.* (2012) demonstrated that Australia (including Oceania) had the highest direct and indirect net exports, followed by Latin America. North America and Africa are also net exporters, though not for every year in the observed period. The large amounts of directly imported fossil fuels are responsible for North America's positive net balance of direct and indirect trade flows. Europe had the largest direct and indirect imports, followed by Asia.

In terms of environmental costs, net-exporting countries experience increased environmental pressures relating to extraction and processing activities, while net-importing countries shift the environmental burden to exporting countries.

3.4 Water embodied in trade

Water is an abiotic, renewable resource that is essential to the sustenance of life on Earth. Indeed, the human body can barely last a week without water. It is also a critical input to human activities ranging from agricultural and industrial production to navigation and recreation. As such, water use holds analytical consistency in terms of water flows into and out of a social system on the same scale as the concepts of social metabolism and material flows. However, since water is very heavy and costly to transport over large distances, it is rarely traded directly. Thus, water flows embedded in products, also known as 'virtual water' or 'water equivalent of traded commodities' in MFA terminology, provides important information on the source of water in social-metabolic processes. Biomass and livestock products, and industrial and energy products are important carriers of virtual water. It is important to establish the relationship between water flows and global trade, because of the differential geography of water availability, its susceptibility to climate change and its ongoing relationship with environmental and human security worldwide (McGlade *et al.*, 2012).

There are several analytical issues characteristic of water in the metabolic interface between society and the environment. Because water serves myriad human activities, it is essential to understand, from the outset, the different definitions of water 'use'. River navigation, for example, entails an in-stream use that requires a certain range of water flow but no actual consumption. Agricultural systems, on the other hand, rely on the evapotranspiration of water, either from rainfall and local soil moisture or from irrigation systems that withdraw water from available sources. Furthermore, water can serve multiple human activities before it is considered no longer useful. For the purpose of this report, we use the definition of consumptive use, taken from Gleick (2003), which "typically refers to water withdrawn from a source and made unavailable for re-use in the same basin, such as through conversion to steam, losses to evaporation, seepage to a saline sink, or contamination."

The quality of water determines its usability, but contamination is often difficult to account for in water use analyses. Challenges arise in appropriately assigning levels of consumptive use to different types of contamination when accounting for water quality in a socio-metabolic context. For example, an industrial system may use clean, fresh water for its operations, and release toxic effluents into a local watershed. The contamination prevents further use of the water in agricultural or domestic contexts, but a downstream thermoelectric power plant could make secondary use of that wastewater for cooling purposes, without making additional demands on local water resources. The sections below will discuss how various methods in the literature handle this concept.

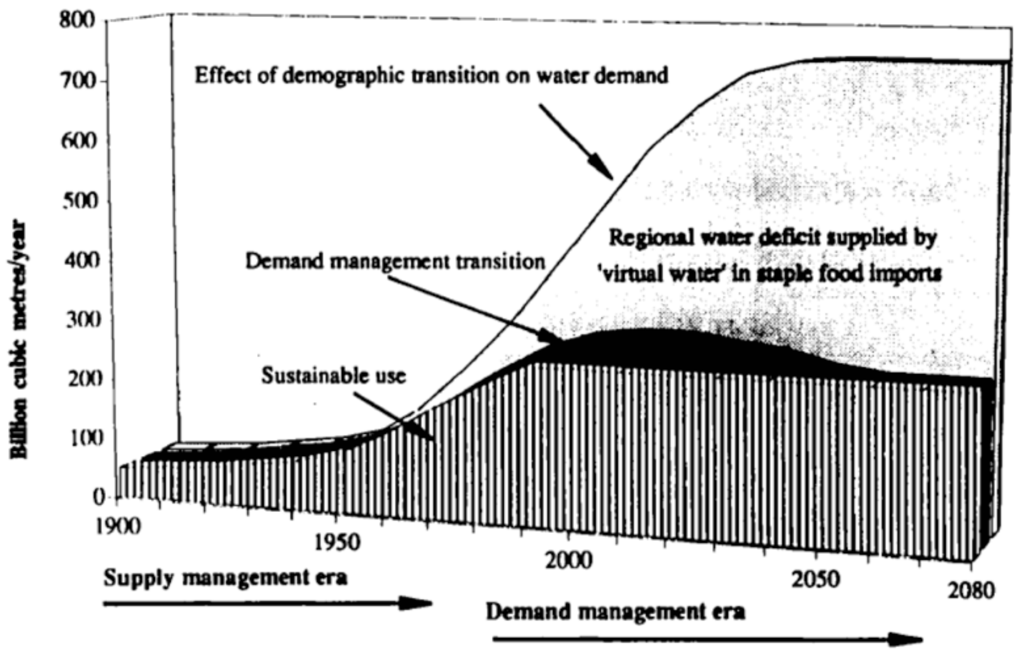
Finally, water consumption should be studied within the context of the cycling of water in the Earth's hydrosphere. The stock of water on Earth (including the atmosphere) is fixed at about 1.4 billion cubic kilometres (km^3). The sun's energy drives the hydrologic cycle, which involves water flows through evaporation, transpiration, precipitation, groundwater recharge and aquifer flows, amounting to about 500 km^3 per year (Trenberth *et al.*, 2007). These processes are highly differentiated geographically, but occur with some seasonal regularity, influenced by natural and anthropocentric drivers. Thus water consumption through human activities implies an intervention into hydrospheric flows, and therefore raises distributional issues, but does not entail any change in the Earth's overall water stock.

With these issues in mind, the remainder of this section discusses the relevant scientific literature on virtual water trade, which has seen a surge in recent years among scientists, economists and policymakers.

The thrust of this interest, and the resulting studies, has revolved around two central themes. One is the study of virtual water as a tool to alleviate water scarcity, most often at the national or sub-national level. These studies generally took place earlier in the chronology of virtual water scholarship, and were concerned more with the political economy of food trade than with the precise science of quantifying virtual water. The second theme has been the study of the role of virtual water trade in reducing the impacts of overall global water use by taking advantage of productivity differences between regions. These studies consider a broader range of traded products and are more concerned with the science of virtual water flows and broader issues of globalization and sustainability. In the following sections we provide details on the methods used to measure virtual water, the main results in the past twenty years, and a discussion on current methodological debates and future applications in this field.

Figure 24

Estimates of water use and availability in the MENA region



Source: *(Allan,* 1996a)

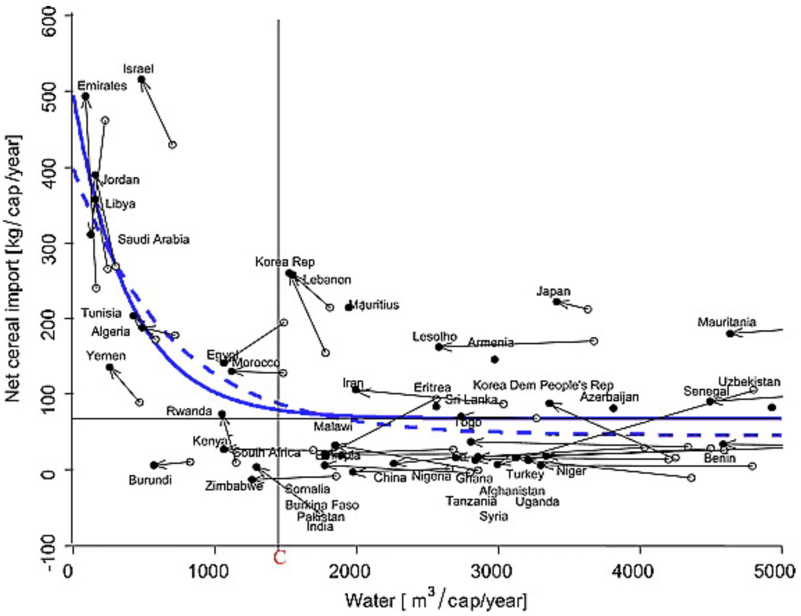
Virtual Water Trade to Alleviate Scarcity

Although some early writings on social metabolism pertained to water, especially with respect to smaller social systems like cities (e.g. Wolman, 1965), the role of virtual water in larger systems has not been studied explicitly in this light. The concept of virtual water can be traced back to the early 1990s, to studies on water-constrained development in the Middle East and North Africa (MENA) region by the British geographer Tony Allan. Allan is credited with having coined the term 'virtual water', as an explanation for the apparent absence of resource conflict among MENA countries (Allan, 1996a). The import of virtual water, mostly in the form of food grains, was found to be an important coping mechanism for domestic water scarcity in light of growing demand (Figure 24).

Allan continued to promote what he called the "economically invisible, politically silent" policy option of virtual water throughout the late 1990s (Allan, 2002, 1998, 1997, 1996b). By the early 2000s, several other authors had begun studying different aspects and applications of 'virtual water strategy'. Earle (2001) applied the concept to the agricultural product trade regimes of four southern African countries, and provided some initial statistical evidence that domestic, renewable water sources – often referred to as the water "endowment" of a country in the literature – was a good explanation of why countries engage in virtual water trade. Yang and Zehnder (2001) found the strategy applicable at the sub-national level, arguing for integration of virtual water into planning decisions on regional scarcity within China. Yang and Zehnder also applied the water endowment thesis (analogous to comparative advantage) to six southern Mediterranean countries (Yang and Zehnder, 2002) and later to all the countries in Africa and Asia. Through their study, Yang and Zehnder (2002) showed that over the previous two decades (1980-2000), countries with strong financial resources increased their imports of virtual water in the form of food grains, to address domestic demand from growing populations (Figure 25) (Yang *et al.*, 2003).

Figure 25

Patterns of change in per capita net cereal import versus per capita available water resources



Source: (Yang and Zehnder, 2007)
Legend: Dashed curve and open circles are the fits of the model with the water variable only for the investigation period 1980–1984, and solid curve and solid circles with country names are the fits for the investigation period 1996–2000. Arrows in the diagram indicate movements of the positions of the countries from thet former to the latter period.

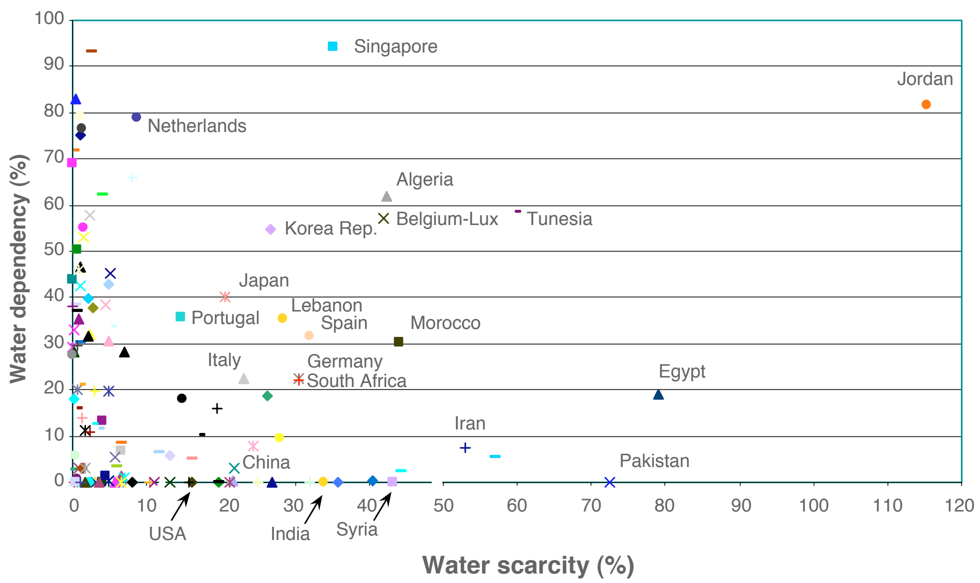
Wichelns (2011a, 2011b, 2010, 2004, 2001) has argued consistently from an economic standpoint against the primacy of virtual water in explaining a region's or a country's trade flows. In his 2001 article, he discussed Egypt's virtual water trade regime, demonstrating that other factors, such as land and labour, as well as the influence of agricultural policies on farmers' valuation of water, were also significant determinants of water use and trade. This helped explain observations from later studies, which showed that, in some cases, virtual water actually flows from areas of low endowment to areas of high endowment, an apparent anti-thesis of the virtual water strategy (Fraiture *et al.*, 2004; Verma *et al.*, 2009). In later papers, Wichelns acknowledged the value of the concept of virtual water from a descriptive analysis standpoint, but argued that, for meaningful correlation in policy prescription, hydrologic indicators such as water endowment are insufficient and that comparative advantage theory must be understood in the context of a greater set of criteria.

Although these initial studies laid the foundations for virtual water as both a strategy and an explanatory factor in trade flows, they were limited in both their contextual geographic applications and their rough quantification of virtual water. The scope of inquiry into virtual water has increased significantly since 2002, when the first attempt to calculate virtual water flows between all countries of the world was undertaken at the Institute for Water Education in the Netherlands. The report (Hoekstra and Hung, 2002), limited to agricultural crops and omitting animal-based or industrial products, provided the basic calculation methods that have been repeatedly used in virtual water studies ever since.

Hoekstra and Hung (Hoekstra and Hung, 2005a, 2002) averaged global virtual water flows in the form of crops from 1995 to 1999 and found that total flows amounted to about 695 cubic kilometres per year (Gm3/y), or about 13 per cent of total global water use. The report also provides virtual water balances for nations, world regions, and continents with respect to indicators for scarcity and "water dependency," defined as the extent to which a country relies on imported virtual water (Figure 26). The results referred back to the virtual water strategy thesis emphasised in earlier works. However, earlier works related virtual water imports to endowment, whereas Hoekstra and Hung relate it to water scarcity, which takes into account the actual degree to which a country's water resources are already being used.

Figure 26

Water dependency versus water scarcity for all countries in the world (1995–1999)



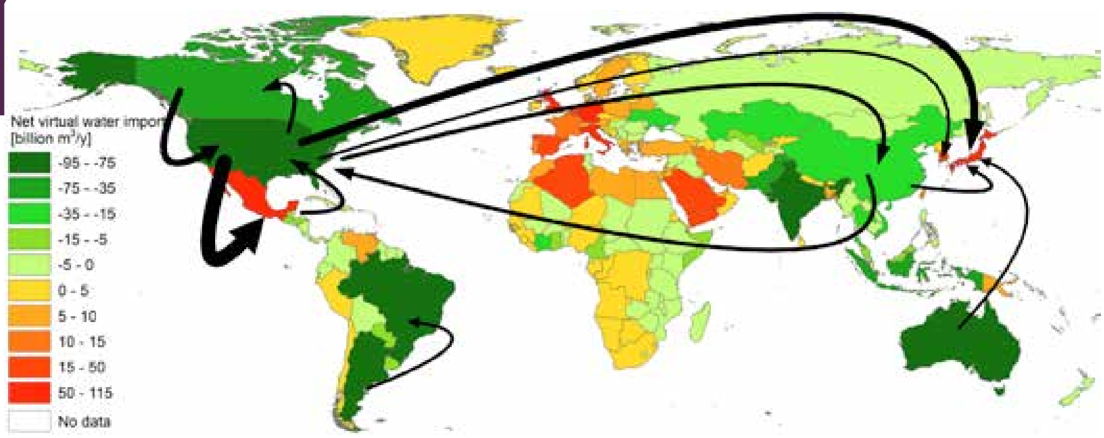
Legend: Water scarcity is defined as the ratio of total water use to water availability; water dependency is calculated as the ratio of the net virtual water import into a country to the total national water appropriation.
Source: (Hoekstra and Hung, 2005b)

These topics, and many others, were addressed in 2002 at the International Expert Meeting on Virtual Water Trade. The proceedings (Hoekstra, 2003) provide evidence of a range of perspectives on the application of virtual water, but also some analytical convergence that helped define the field, as it developed further. While regional assessments were still important contributions to the literature, it was acknowledged that virtual water trade is clearly a global phenomenon and should be studied as such.

Mekonnen and Hoekstra (2011) calculated upstream water requirements (virtual water flows) of traded goods for nearly every country in the world between 1996 and 2005. Average net virtual water import per year and major bilateral flows are shown in Mekonnen and Hoekstra, 2011, Figure 27Error! Reference source not found.. Country-specific patterns are similar to results from material flow studies, but climatic and bio-geographical conditions add another perspective. Most European, Middle Eastern, and North African countries are net virtual water importers, with Japan, South Korea, and Mexico emerging as the most important importers. The largest virtual water exporters are in North and South America, as well as South and South-East Asia, and Australia.

Figure 27

Virtual water balance per country and direction of gross virtual water flows related to trade in agricultural and industrial products over the period 1996–2005



Source: (Mekonnen and Hoekstra, 2011). Only the biggest gross flows (>15 Gm3⁄y) are shown.

Statistics from Mekonnen and Hoekstra (Mekonnen and Hoekstra, 2011) demonstrate that among 66 virtual water exporting countries (83 per cent of the net water exporters group), net exports of water were less than 30 per cent of domestic extraction for consumptive use. The countries that export the largest shares of domestic extraction include Kazakhstan (30 per cent), Canada (33 per cent), Argentina (48 per cent), Côte d'Ivoire (50 per cent) and Australia (56 per cent). Among the approximately 94 net virtual water importing countries, 53 derive less than 30 per cent of consumptive water from imports. Notable countries whose net import to consumption ratio exceeds 30 per cent include South Korea (57 per cent), Japan (67 per cent) and most European countries, with the United Kingdom (78 per cent) accounting for the largest share. These statistics show averages from 1996 to 2005 for crop, animal and industrial products only.

Virtual Water Trade to Reduce Global Water Use

This body of research considers the water efficiency of the overall global production system, as well as factors that control or distort that efficiency. When countries are linked through international trade, global water savings can be facilitated by the optimization of geographical differences in water productivity. Virtual water savings through trade occur when the import of a product results in lower water use than would domestic production of the same product. The savings are potentially the result of differences in climate, soil fertility or production technologies, which affect the yield-to-water input ratio (productivity). Aggregating country-level savings amounts to global savings, which theoretically frees up water for more immediate needs, such as drinking, sanitation or the environment.

Several authors began exploring the notion of global water use efficiency in the mid-2000s. Fraiture *et al.* (2004) calculated global water savings related to trade in cereal products in 1995 to be 112 km3. The authors caution, however, that savings are mostly a by-product of trade that takes place for reasons other than water endowment and, as global trade increases in the future, it is unlikely to free up water where it is needed. Oki and Kanae (2004) include a broader set of products (including meat, soy and barley) and take the long-term perspective, calculating the trajectory of global savings since 1961 to have increased steadily from almost zero to over 450 km3 by 2000. Yang *et al.* (2006) omitted meat, but analysed the virtual water trade of a broader array of crop types averaged over 1997–2001, finding that virtual water savings amounted to 336 km3. The authors also attempt the first uncertainty analyses in global virtual water flows analysis, showing that calculations are highly sensitive to real world crop production factors (water deficit or excess at the field level), for which there are limited data.

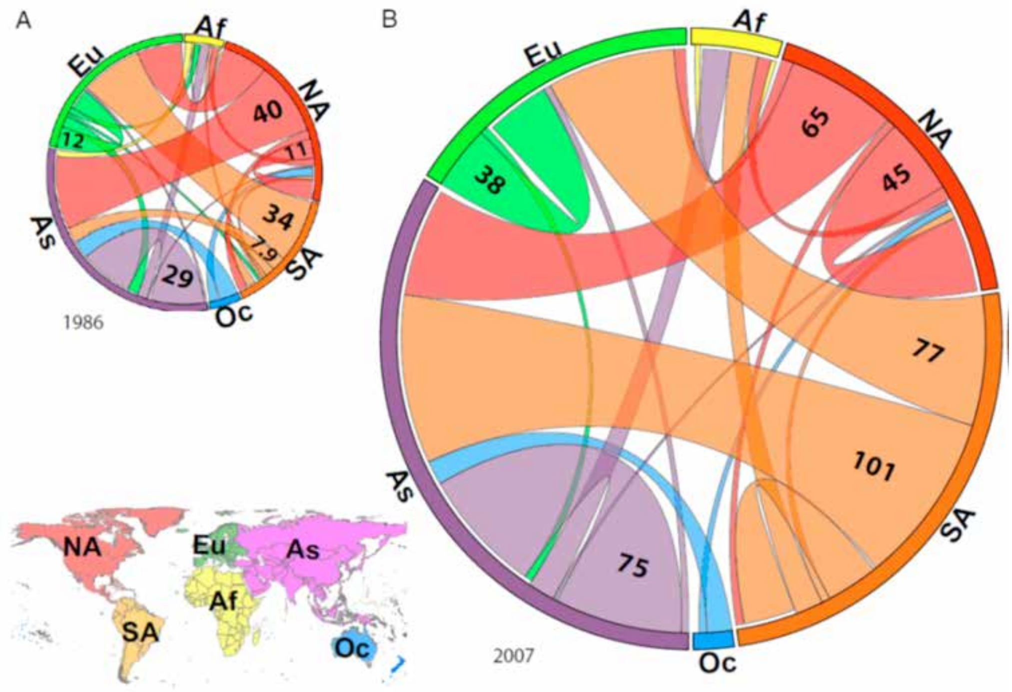
Subsequent work on global virtual water trade has attempted to improve on the methodology of the initial studies in a number of ways. The uncertainties surrounding the virtual water content of crops gave rise to several modelling efforts to characterize more spatially explicit variables (Fader *et al.*, 2011; Hanasaki *et al.*, 2010; Liu and Yang, 2010; Rost *et al.*, 2008; Siebert and Döll, 2010). Another important aspect, initially indicated by Fraiture *et al.* (2004), is the difference between green water and blue water savings. For global water efficiency, it would be desirable for exporting countries to rely more on rain-fed (green water) agriculture and to save irrigation (blue) water use in importing countries (Aldaya *et al.*, 2010; Chapagain and Hoekstra, 2008; Yang and Zehnder, 2007). However, a potential trade-off could occur, if more land were required for rain-fed than for irrigated production.

Several authors have adopted a critical perspective and have further refined the structure and logic of the virtual water trade system. D'Odorico *et al.* (2010) developed a simple model of the virtual water trade network, in order to test long-term resilience to shocks such as drought. The authors concluded that globalization provided short-term benefits via virtual water but has also resulted in lower resilience, owing to the locked-in interdependencies that make dynamic virtual water transfer difficult. Konar *et al.* (2011) and Suweis *et al.*, (2011) have developed a more formal predictive model. Using 'complex network theory', the authors have established that the virtual water trade network operates on a hierarchical model, with water-endowed countries forming trade clusters. These clusters will be increasingly difficult for water-scarce countries to penetrate, under climate-change scenarios. Yang *et al.* (2012) came to similar conclusions, using ecological network analysis. Dalin *et al.* (2012) build on the modelling of Konar *et al.* (2011), tracing the evolution of the virtual water trade network since 1986(Dalin *et al.*, 2012, Figure 28), to identify contributory political-economic factors like trade agreements in the changing formation of the network.

Ansink (2010) endorsed Wichelns' critique (Wichelns, 2011a, 2011b, 2010) of virtual water being insufficiently integrated with comparative advantage theory, by applying the Heckscher-Ohlin model to refute claims that virtual water trade has the potential to redistribute water resource benefits according to endowment and to reduce conflict. More recently, Reimer (2012) has attempted to establish virtual water as an acceptable economic concept, by situating it as an example of "services of factors" that are determined only latently by the water endowments of trading partners.

Figure 28

Virtual water flows between the six world regions



Source: (Dalin *et al.*, 2012)
Legend: Numbers indicate the volume of VWT in km^3, and the colours of the links correspond to the exporting regions (colour scheme given bottom left). The circles are scaled according to the total volume of VWT. Note the large difference between total VWT in 1986 (A; 259 km^3) and in 2007 (B; 567 km^3)

These ongoing developments provide a trail of maturation in the study of virtual water over the last 20 years. Virtual water has proved to be a strong, if only partial, explanatory factor in how water-stressed countries and regions have coped with the rising demand stemming from population expansion and development. This strategy may have limited application from a policy perspective and is far from being a realistic criterion for optimizing trade systems. Nevertheless, the literature, generally, indicates that virtual water trade flows provide an important descriptor for the interaction between the hydrosphere and the global economy.[20]

20 The UNEP report "Measuring water use in a green economy, A Report of the Working Group on Water Efficiency to the International Resource Panel" (McGlade *et al.*, 2012) provides further information about measuring water use in a global "green economy".

3.5 Conclusions on upstream requirements of traded commodities

The upstream resource requirements of trade are generally on the rise, irrespective of the methodology of accounting used for calculations. Different factors have influenced the growth in upstream requirements. Firstly, higher-processed goods represent an increasing share of total trade. Secondly, trade activities in general have increased, such as the trading of more intermediate goods between countries, together with the additional transport, before final demand is satisfied. At the same time, declining ore grades for metals and industrial minerals, as well as declining energy returns on energy investment (EROEI) for fossil fuels (see Chapter 4.3), raise upstream requirements for these commodities, since they require higher material and energy inputs per ton of tradable good. The increasing consumption of fossil energy carriers for fuelling transport is another factor driving growth in upstream requirements. Finally, population growth and increasing food demand in arid regions require increasing imports of crops and corresponding increases in "virtual water" embodied in trade. These factors may outweigh any possible decline in resource use achieved by a potentially better allocation of extraction and production processes in the global economy.

There is a pronounced difference in the international distribution of upstream resource requirements between high-income (and high-consumption) countries and low-income countries. This difference is greater than that relating to direct trade flows. Trends point to increased externalization of resource-intensive processes from high-income countries to developing and emerging economies and, through this, a prolongation of the direct trade patterns that were prevalent in the 20th century. Changes to direct trade patterns in recent years, i.e. industrialized countries specializing in net exports, are no longer apparent when upstream material requirements are considered. However, rapid developments in the analysis of upstream requirements, in particular for materials, could yield new insights in the coming years.

Credit: Jimmy Harris, flickr

4. Trade flows by type of resource and their environmental impacts

4.1 Biomass trade and upstream requirements, including land-use

Availability of resources is at the very interface of society-nature interaction and societies have a long history of converting natural terrestrial systems into increasingly human-dominated ones (Boserup, 1993), thus maximizing the output useful for sustaining human life. Biomass materials are considered to be the renewable resources that comprise all raw materials of plant origin extracted from nature as well as hunted animals. This includes agricultural products, harvest by-products (e.g. straw), grassland harvests, biomass grazed by livestock, timber and hunted (wild) animals. Plant-based biomass makes up most of the socio-economic uses of biomass, hence extraction is closely linked with harvest land.

Biomass is mostly a flow through the economy, i.e. it is consumed within one year as human or animal food, chemically split and transformed into gaseous emissions (mostly CO2) or solid wastes. Only a negligible fraction accumulates in societal stocks such as timber used for construction purposes, paper and other more durable goods made out of fibres such as textiles. Human nutrition continues to be the primary socio-economic use of biomass. Around three-quarters of biomass extraction directly or indirectly takes the form of human food (of which one-third ends up as food waste). Other significant uses of biomass materials include raw materials for industrial production and for construction purposes, and, increasingly in recent decades, energy provision. The fundamental role of biomass for nutrition plots a strong correlation between biomass use and population figures, but only a weak correlation with GDP. In accounting for biomass imports and exports, all traded commodities, including animal-based products such as meat, fish, milk, eggs, leather, etc., are recorded.

Biomass production comprises the largest share of human land use, with food production playing a central role. This is reflected in the accounts for land cover/use: in 2010, 38 per cent of the total global land surface was in use for agriculture, with 12 per cent consisting of croplands and 26 per cent of pastures (FAO, 2012). According to FAO's latest forest resource assessment, 31 per cent of the total land area in 2010 was forested (FAO, 2010). This area includes a wide range of lands, from areas with a mere 10 percent of tree cover to dense tropical primary forests. The lion's share of these forests, however, is used by humans: just about one-third of forest land was made up of primary forest in 2010 (FAO, 2010). The remaining 31 per cent of the global land area is typically of low quality, such as deserts or marginal grasslands. Urban and infrastructure areas currently cover about 0.5 per cent of the global land surface (Schneider *et al.*, 2009) or 2 per cent, according to the UNEP land report (Bringezu *et al.*, 2014).

Biomass materials are considered to be abundant, as they can be extracted all over the globe. However, production is concentrated, owing to differences in land availability and land productivity. For example, one hectare of fertile cropland can produce food for a large family, but the same area of low-quality land can hardly produce any biomass output at all, unless massive, costly colonization measures, such as irrigation, fertilization, and intervention into crops and weeds, are undertaken. With a share of 15–20 per cent of materials traded around the globe, trade in biomass is lower than that of fossil fuels (40–50 per cent) and metals (20 per cent), but still significant. However, in relation to the total biomass extracted from land, trade is of minor importance, accounting for only 8 per cent of the extracted amounts (DE). For the other two material groups, fossil fuels and metals, this fraction is much higher, standing at around 40 per cent.

Overuse, which can lead to the extinction of species, is a more direct threat to biomass than scarcity or exhaustion. A large number of the most pressing environmental impacts are directly associated with land-use and the provision of biomass: for instance, biodiversity loss, loss of biomass carbon storage capacity, soil degradation, eutrophication and pesticide contamination. Land degradation, i.e. any reduction or loss in the biological or economic productive capacity of the land caused by human activities (UNCCD, 1994), can limit potential biomass extraction (Zika and Erb, 2009).

Using land area as a measure of human impact on natural systems can obscure the fact that land can be managed at varying intensities by humans; think, for example, of an intensely managed cropland versus an extensive grassland. The human appropriation of net primary production (HANPP) indicator presents a framework to include such land-use intensity aspects across different types of land-use and land cover. HANPP indicates land-use intensity by measuring human alteration to biomass availability in ecosystems through land-use practices. To do so, prevailing levels of net primary production after harvest activities are compared to a hypothetical value in a reference system without the human presence. The approach includes harvested biomass in a comprehensive way as well as human-induced changes in ecological productivity of the land, like the building of settlement areas. While the first component (extraction through harvest) is included in a similar way in calculations relating to the total material requirements of biomass products in MFA studies, the second component is unique to the HANPP approach.

In contrast to minerals, the processing of plant-based biomass materials results in minimal biotic wastes along the production chain (FAO, 2003).[21] Many by-products or potential wastes are used as bedding material or fodder, or else left on the field for reintegration into the soil through ploughing. As for animal products, high "losses" in the early stages of "processing" are a given, because of the conversion from plant to animal biomass.

Direct trade flows

In 1900, biomass was still the major resource used by societies, as a source of nutrition as well as for construction and energy provision. Global biomass use stood at 5 billion tons in 1900 (Krausmann *et al.*, 2009), which represented 75 per cent of all material use. By 2010, biomass use had increased to 21 billion tons.

21 Household-level food wastes, which can be over 30% percent in developed economies (Gustavsson *et al.*, 2011), are typically included in national food supply (consumption) data (FAO, 2001).

However, a decrease in its relative importance has reduced total material use to 30 per cent. Biomass materials are homogeneous in terms of their chemical composition [hydrocarbons] but still comprise different biomass materials. The major share of biomass used comprises crops (36 per cent, cereals, vegetables, roots, fruits, etc.) and crop residues (20 per cent, mainly straw and beet leaves), followed by fodder crops (6 per cent), grazed biomass (26 per cent) and timber (11 per cent). Fish catch is relatively small, compared to total biomass extraction, amounting to only 0.4 per cent.[22] In 1950, not far short of 40 per cent of all biomass was extracted in the 2010 group of OECD countries[23] (35 per cent), followed by Asia (30 per cent), Latin America (14 per cent), Africa and the former USSR (10 per cent each), and the Middle East and North Africa (2 per cent). By 2010, the relative dominance of OECD and former USSR countries decreased slightly (to 25 per cent and 5 per cent, respectively) while extraction activities shifted to Asia (now at 37 per cent). Individual countries with the highest extraction are China (14 per cent of global biomass extraction), India and Brazil (10 per cent each), the USA (9 per cent) and the former Soviet Union (5 per cent). Overall, global biomass extraction and use increased by +150 per cent from 1980 to 2010 (or +330 per cent from 1950 to2010) (Dittrich, 2012).

Biomass trade increased from 641 million tons in 1980 to 1,721 million tons in 2010 (+168 per cent). Food, in particular cereals, has consistently held the highest share in traded biomass in the past three decades, reaching around 47.3 per cent (share of cereals: 22.6 per cent) in 2010. Products made from biomass, including paper and beverages, held the second highest share, at 25.7 per cent in 2010, followed by forestry products (17.5 per cent), feed (9.7 per cent) and animals and animal-based products (8.7 per cent).

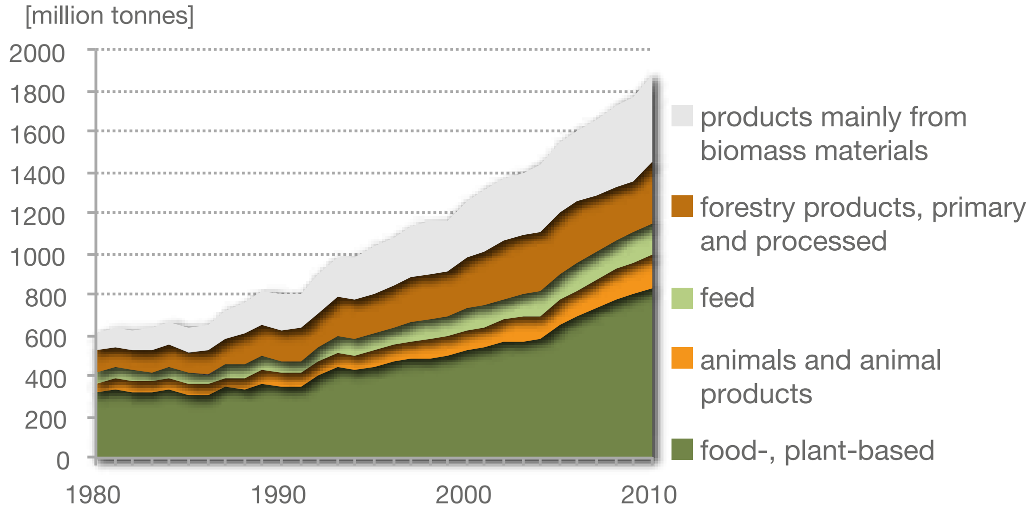
The highest increases can be found in trade in products made mainly from biomass (+352 per cent between 1980 and 2010), followed by trade in feed (+272 per cent), animals (+262 per cent), wood (+160 per cent) and food (+146 per cent). At a more disaggregated level, trade in meat, meat preparation and fish catch witnessed an above-average increase of +429 per cent and +363 per cent respectively, during the same period.

22 In MFA, only fish catch and hunting are considered in biomass extraction. Other biomass, from livestock or from aquaculture, are by definition considered part of the socio-economic system, so that only the biomass used for feeding these animals is accounted for as biomass extraction (Eurostat, 2013, p. 201).

23 The 2010 group of OECD countries

Figure 29

Trade in biomass by main sub-category, 1980–2010

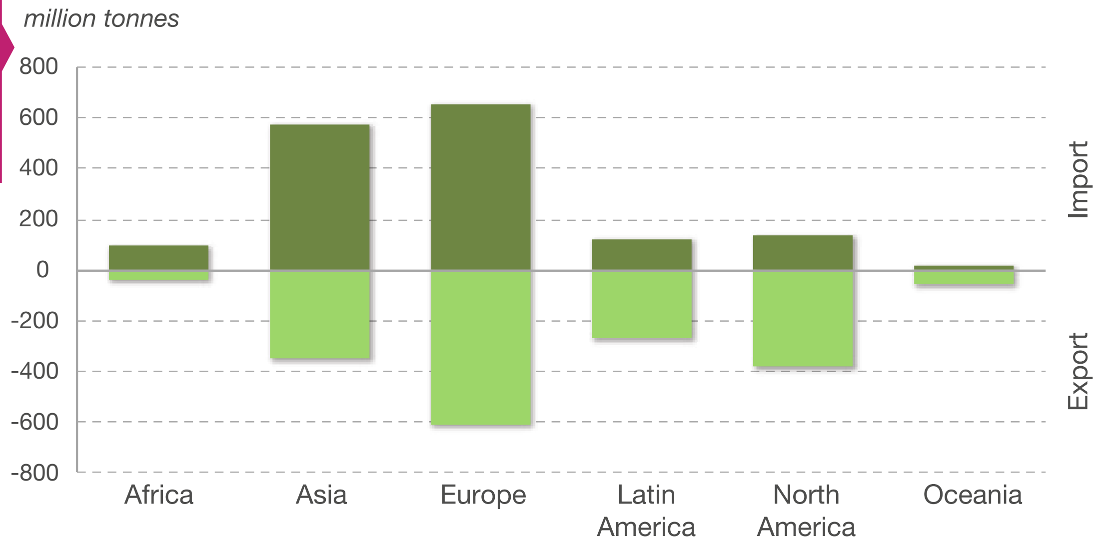


Source: (Dittrich, 2012); note: trade is based on exports, because export statistics of biomass are more complete in terms of country and commodity, and have a better coverage than imports.

The total volume of biomass trade, for imports and exports, was highest among European countries (among other reasons, owing to inner-EU-trade), followed by Asian and North American countries (Figure 31). North America was the largest net supplier of biomass, with 246 million tons in 2008, followed by Latin America and Oceania. Asia was by far the dominant net importer, with 225 million tons, followed by Africa and Europe. This geographical distribution follows patterns of population density; countries of high population density usually require additional biomass imports to satisfy domestic demand, whereas low population density countries appear to have land area and labour available for large-scale biomass production and exports. Additionally, other factors, such as transportation infrastructure, access to technology, conflicts, etc., influence production and trade patterns, as witnessed in some African countries, for example.

Figure 30

Biomass-based commodity trade between countries, by continent, 2008



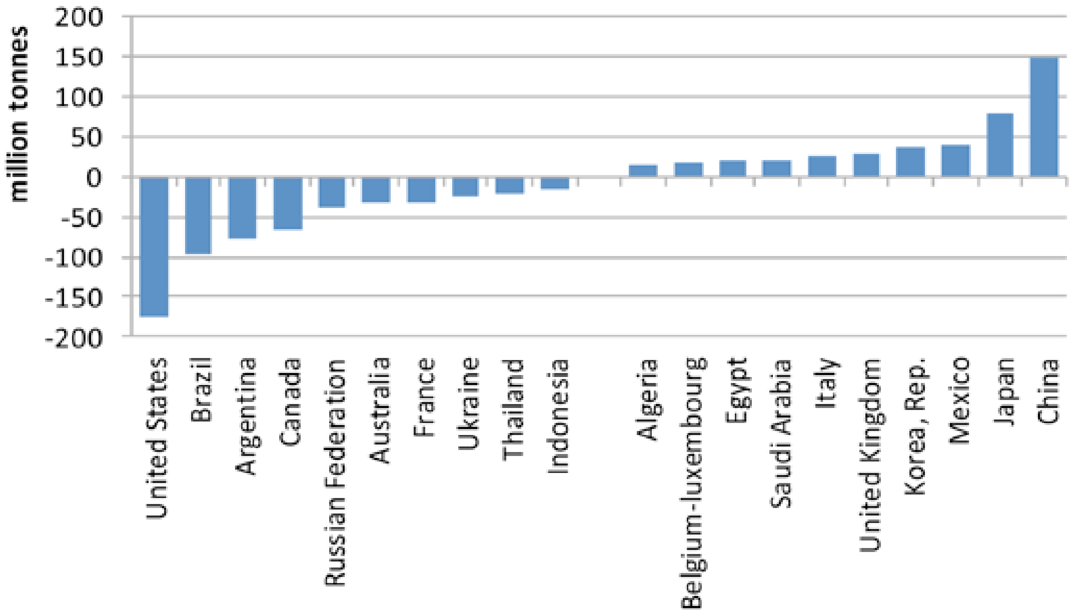
Source: (Dittrich *et al.*, 2012)

At country level, the biggest suppliers, as measured in total exports in 2010, include the US (273 Mt), Brazil (114 Mt), Canada (98 Mt), as well as Germany (92 Mt), France (86 Mt), Argentina (81 Mt) and the Russian Federation (67 Mt). The biggest demanders/importers in 2010 were China (205 Mt), Germany (98 Mt), the US (97 Mt), Japan (90 Mt), the Netherlands (70 Mt) and Italy (60 Mt). In terms of net trade (measured as physical trade balance, PTB), the largest net suppliers of biomass are the US (176 Mt), Brazil (99 Mt), Argentina (78 Mt), Canada (66 Mt) and the Russian Federation (39 Mt). China (150 Mt), Japan (79 Mt), Mexico (40 Mt), South Korea (37 Mt) and the United Kingdom (29 Mt) are ranked as the highest net demanders of biomass products.

Temporal trends in direct trade show that it has grown considerably faster than biomass production (average annual growth rates of 4 per cent versus 2 per cent, from 1961 to 2009 (FAO, 2012)), evidence of the increasing impact of international trade on land-use systems. However, crop yields increased, as well, during this period and mitigated the impact on areas and HANPP linked to trade. Data from Kastner *et al.* (2012) for vegetal food items (i.e. excluding production and consumption of animal products) show that from 1961 to 2007 the share of cropland linked to international trade within the global total increased from 10 per cent to 17 per cent, or from 51 Mha to 121 Mha.

Physical biomass trade of the top 10 net-importing and net-exporting countries

Figure 31



Source: *(Dittrich,* 2012)

Upstream requirements of biomass materials (IO-based approaches)

In 2010, 15 per cent of global biomass materials extraction was traded, compared to 10 per cent in 1970. If upstream material requirements are considered, the share of biomass materials directly or indirectly related to trade increased to 25 per cent (Bruckner *et al.*, 2012). This means that 25 per cent of all biomass materials globally extracted is – directly or indirectly – redistributed to satisfy foreign demand (intermediate use not included). However, this figure also includes trade for intermediate uses in the production system and thus accounts for multiple deliveries before the biomass materials are used in a final consumption good. However, considering that only a part of the total extraction is traded to satisfy final foreign demand, the traded fraction is proportionately reduced to 7 per cent for 2010 and 4 per cent for 1970. Upstream biomass requirements grew by 20 per cent (Bruckner *et al.*, 2012), which is a significant rate but nevertheless much lower than for upstream requirements of other material categories such as metals and industrial minerals (+90 per cent), construction minerals (+60 per cent) and fossil fuels (+45 per cent).

Latin American countries are important biomass exporters to global markets. Their net exports have increased significantly; even more so, when upstream requirements are considered (see Muñoz *et al.*, 2009; Wiebe *et al.*, 2012). Low population density and favourable resource endowment, such as productive land, support their specialization in biomass production and exports. In the case of Colombia and Brazil, for example, Muñoz *et al.* (2009) showed that net export volumes, comprising mainly biomass materials, more or less doubled (by a factor of 2 for Colombia and a factor of 1.5 for Brazil). The European Union, on the other hand, has a more or less balanced physical trade with respect to biomass goods. Recalculating trade as RME does not change the pattern, implying that Europe is considered self-sufficient in terms of biomass materials and thus biomass trade (Schoer *et al.*, 2012).

Other material upstream requirements for producing biomass goods (LCA-based approach)

In the production of biomass goods, other materials such as fossil energy carriers for fuelling tractors and machinery in industrial agriculture, fossil fuels for producing fertilizers, metals contained in machinery and production sites, non-metallic minerals for building roads and agricultural buildings, etc. are also used. As LCA methodologies apply a product-based approach, they are comprehensive in accounting for all materials used in the production of biomass products.[24]

Currently, almost 25 per cent of all upstream material requirements are associated with traded biomass goods (Dittrich *et al.*, 2012; note that erosion is included as unused extraction in this calculation). Biomass products that require higher amounts of materials in the upstream production process include vegetable fats and oils, in particular palm oil. "Direct trade with palm oil increased by a factor of 30 between 1970 and 2005, resulting in nearly 24 million tons of direct flows and around 1,344 million tons of ecological rucksacks in 2005" (Dittrich *et al.*, 2012, p. 35). However, biomass trade and upstream requirements for biomass trade pose significant challenges in some areas of accounting. The method of allocating processed goods to primary products greatly affects results of consumption-based accounts for biomass. Official statistics report harvest of commercially valuable parts such as soybeans, wheat, or wood. From these, soy oil, bread and furniture are produced, respectively. In most cases, the by-products of the production processes are valuable inputs for other uses, such as oil cakes and bran as livestock feed for meat production, and sawdust/wood residues for the paper industry. In view of this, the allocation choice will greatly affect the results, when processed biomass products are linked to primary products, upstream requirements and land-use. Existing studies use different approaches for this allocation, basing it, for instance, on monetary value, dry matter content or assigning all impact to a so-called "main product". The latter approach can be problematic: for instance, if all land-use is assigned to soybean oil and none to the oilseed cake, the actual impact of animal products, for which oilseed cakes are vital inputs, will be greatly underestimated.

24 The LCA approach referred to here includes unused extraction (for every component that has been used for the production of the commodity), which makes it difficult to relate its results to direct trade or domestic extraction, as system boundaries differ.

Upstream water requirements of biomass products

Water is a necessary input for biomass production, and can be divided, for analytical purposes, into two sources. Firstly, "green water" is the precipitation and soil moisture that is used directly in biomass production, as in rain-fed agriculture. Secondly, "blue water" is surface or groundwater that is physically applied to biomass production, as in irrigated agriculture. Green water dominates global biomass production for human consumption, accounting for 75 per cent of water use in global agricultural production (Falkenmark and Rockström, 2006).

Globally, the agricultural sector accounts for the largest share of both water withdrawal (66 per cent) and consumptive use (85 per cent) (Shiklomanov, 2000). When it comes to embodied water use in traded products, most studies focus on consumptive use as the more appropriate indicator, since withdrawn water that is not consumed can still be used for other productive purposes. Biomass production necessarily entails evapotranspiration, and the total amount of water consumed through a plant's productive cycle is called its "crop water requirement." Crop water requirements differ according to crop, location, climate and other growing conditions. Several models exist for estimating green and blue crop water requirements, for example FAO's CROPWAT model.

Crop water requirements can be related to biomass trade flows through production and yield statistics for specific crop products, available through FAO. For example, the amount of green and blue water consumptively used by a one hectare maize field in a given location and set of growing conditions can be related to the quantity of maize grain produced by that same hectare, thereby giving coefficients of green and blue water volume per mass of maize. When countries trade in agricultural products, the upstream crop water requirements can be said to remain embodied within that product. In the case of livestock, green and blue crop water requirements of fodder and forage are often attributed to the livestock products, giving extremely high embodied water coefficients on a volume per mass basis.

As discussed in Section 3.4, a number of researchers have endeavoured, over the past decade, to estimate the volumes of water embodied in global trade, particularly biomass trade. Recent estimates of total upstream water requirements of traded agricultural products range from 567 km3 (Dalin *et al.*, 2012) to 1,654 km3 (Hoekstra and Mekonnen, 2012), depending on the methods used and the assumptions made. As is to be expected, the patterns of embodied water trade generally correspond to patterns of direct biomass trade flows, with North America being the largest net exporter and Asia being the largest net importer (Hoekstra and Hung, 2002). However, contextualizing the on-the-ground social and environmental impacts that these flow volumes represent continues to be the subject of much debate within the LCA and water footprint communities.

Distribution of productive land area

Land as a resource cannot be traded physically, either internationally or domestically.[25] This implies that land resources, domestic or foreign, linked to resource consumption are always “embodied”.[26] Studies that make land resources embodied in international trade their primary focus are fewer than studies on other resources.[27] Among them, the studies are commonly focused on land resources embodied in trade of agricultural and forestry products, owing to the dominant use of land in biomass production (see details below).

Land productivity and availability differ around the world. Figure 32 shows the distribution of land resources across 11 world regions. Regions are ranked according to per capita land availability, from those with the highest availability (North America and Oceania, at almost 8 ha/cap) to those with the lowest (southern Asia with less than 0.5 ha/cap). By accounting for the number of people in each region (on the x-axis), the graph also shows the absolute values of available land area per person. This demonstrates that the regions with the widest bars (i.e. largest populations), eastern Asia and southern Asia, are the ones with the lowest per capita land availability. In general, the Americas (and Oceania) exhibit very high availability of land, with Central America and the Caribbean constituting an exception. Land availability is also high in Sub-Saharan Africa and Northern Africa, and Western Asia. The EU15+ region exhibits quite low levels of land availability, less than 1 ha per capita, while the region of the former Soviet Union and other Europe ranks a high second in per capita land availability.

The numbers in Figure 33 are of limited use, however, when investigating the potential for the production of land-based products. Figure 34, therefore, shows a more differentiated picture, disaggregating the same type of graph as in Figure 33 for the following categories: agricultural land area (permanent pastures, meadows and cropland), cropland area, forest area, and area suitable or very suitable for cereal cultivation with a mixed level of inputs (Fischer *et al.*, 2001).

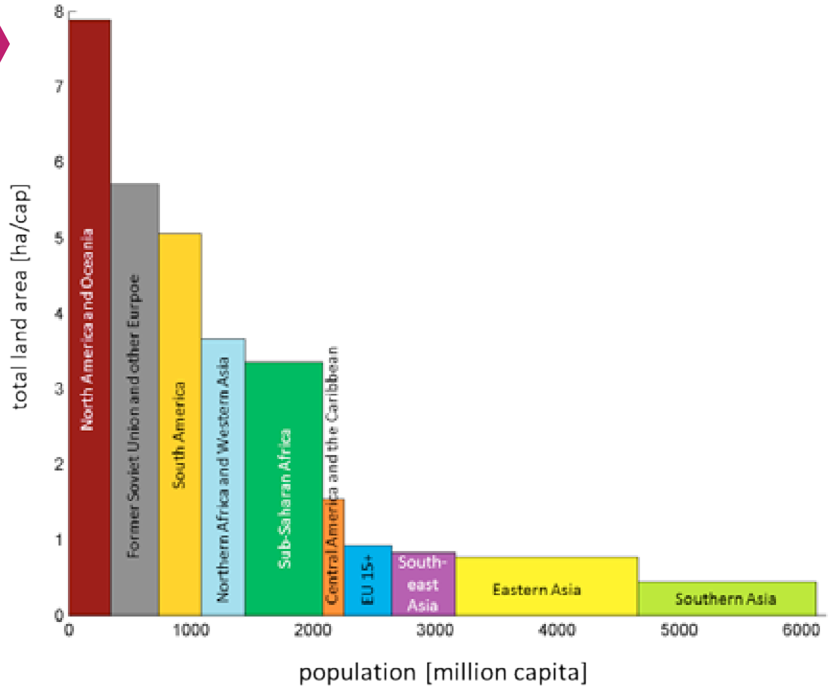
25 A nation can only extend its territory at the cost of other nations, a situation which is often linked to armed conflict and wars. Recently, there has been widespread discussion about nations/companies trying to secure long-term land rights on foreign territories (“land grabbing”). As long as traded products grown on these lands continue to be included in official trade statistics, they will be included in assessments of land embodied in international trade.

26 We use the term ‘embodied land’ here. Sometimes, terms such as ‘virtual land’ or ‘place-oriented ecological footprints’ are used; we consider these terms to be synonyms.

27 The vast literature on ecological footprint accounts, which also often makes trade between nations the centre of attention, uses a measure of land area, hectares, as the common denominator; however, this indicator cannot be considered as a measure of real land demand, as it includes both actual and hypothetical land areas (so-called energy land, the land that would be needed to absorb emissions from fossil fuels through biomass). Additionally, the standard calculation for ecological footprints uses global average values for land productivities, representing therefore mainly a reflection of differences in consumption patterns and lifestyles. In this overview, we only include ecological footprint studies that focus on actual land (as opposed to hypothetical energy land) and that try to assess consumption linked to land demand on the basis of country-specific levels of land productivities, i.e. yields (as opposed to approaches that rely solely on global average values).

Figure 32

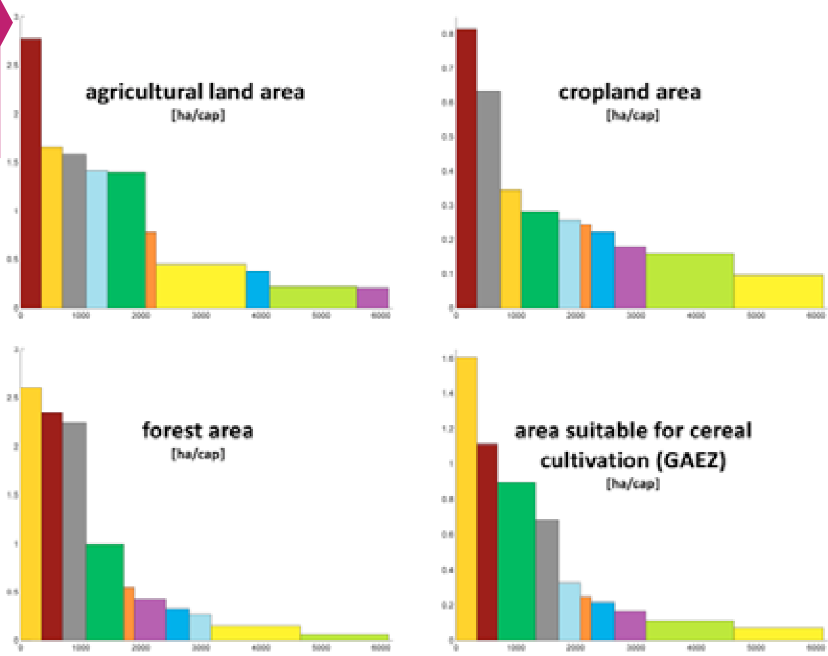
Distribution of land resources across world regions for the year 2000



Legend: The height of the bars represents the amount of land available per capita, the width the number of people in the respective region. It follows that the area of each bar represents the total amount of available land.

Figure 33

Distribution of land resources and land potential across world regions for the year 2000



Legend: note the different scales on the y-axes; colour codes: brown: North America and Oceania, grey: Former Soviet Union and other Europe, dark yellow: South America, light blue: Northern Africa and Western Asia, dark green: Sub-Saharan Africa, orange: Central America and the Caribbean, middle blue: EU15+, purple: South-east Asia, pale yellow: Eastern Asia, pale green: Southern Asia.

Agricultural area (Figure 35 top left) would potentially be an interesting measure of productive land. However, its explanatory value is limited due to very different definition and interpretation of pasture land (Erb *et al.*, 2007). For instance, in Eastern Asia these data contain desert lands with virtually no use for livestock production (Erb *et al.*, 2007). On the other hand the productive grasslands of South-East Asia are most likely underreported in these statistics (e.g.

Kastner, 2009 reports a grassland area of more 6.5 million hectares in 2000 for the Philippines, compared to the 1.5 million of pasture area reported by FAO, 2012 for the same year).

The picture for the global distribution of croplands (Figure 33 top right) represents a more reliable account, owing to the central role of croplands in food supply and security. North America, Oceania, the former Soviet Union and Europe can offer considerable land area per capita, whereas south and east Asia report the lowest values of land area per capita. The use of cropland in North America and Oceania is over eight times higher than in eastern Asia in per capita terms. Figure 33 (lower left) shows South America, with its large surviving tropical forests, as the region with the highest forest area per capita. It is followed by North America, the former Soviet Union and Eastern Europe, regions which have huge boreal forest areas. The recent rates of accelerated deforestation in South-East Asia and southern Asia show these regions as having lower forest per capita levels, despite being known as tropical forest cover and temperate forest regions, respectively. The situation is particularly acute in southern Asia, where only about 0.06 ha of forest land per capita is available.

The lower right chart of Figure 33 shows the distribution of lands identified as being suitable or very suitable for cereal cultivation with mixed inputs (Fischer *et al.*, 2001). South America comes out on top again in per capita availability, followed by North America, Oceania and Sub-Saharan Africa. It is interesting to note that the regions with the largest difference between the values of land with potential for cereal cultivation and the values for actual cropland area in 2000 were the ones with the largest areas of remaining tropical forests: South America and Sub-Saharan Africa. In contrast, in the densely populated Asian regions, the cropland areas were greater than land areas identified as suitable for cereal cultivation. The lower part of Figure 34 offers an alternative metric for the potential of biomass production from land resources: it shows the distribution of potential net primary production (NPP) across the world regions. The picture is quite similar to the one based on the GAEZ data, most likely owing to the fact that cultivation potential and NPP are often closely linked.

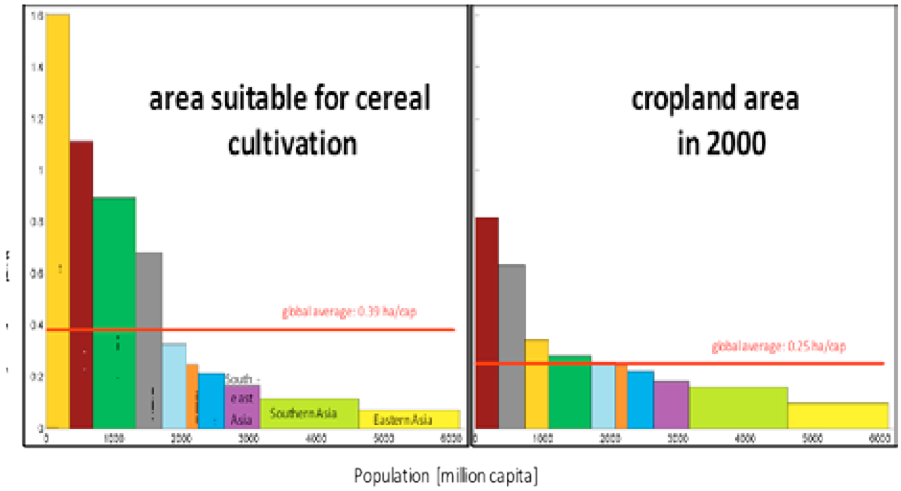
From Figure 32 and Figure 33, it is apparent that, in terms of per capita values, land resources and the potential for biomass production are distributed unevenly across world regions. With respect to the relevance of this report, the analysis implies that trade in biomass products can play a decisive role, if these differences in per capita land endowment are to be lowered. Global accounts of the impact of this trade on such distribution issues are rare (see below). In general, accounts of biomass trade, find flows from regions with high per capita land availability to those with low land availability (e.g. Erb *et al.*, 2009; Haberl *et al.*, 2012; Kastner *et al.*, 2011; F. Krausmann *et al.*, 2009). These flows compensate for the differentiated endowments of land suitable for agricultural production. With respect to lands linked to international trade flows, Kastner *et al.* (2012) state that about 16 per cent of global cropland area was linked to international trade in 2005 (note that this excludes re-exports and does not account for cropland linked to the trade of animal products; it does, however, include trade in feedstuff).

Figure 34 compares land potentially suitable for cereal cultivation (according to Fischer *et al.*, 2001) to actual cropland areas for ten world regions in the year 2000. The figure reveals that, in terms of per capita values (and thus starting from the uneven distribution of population), cropland resources are distributed unequally across the globe and that the distribution of land with cultivation potential is even more skewed than current cropland patterns. Densely populated areas use nearly all land deemed suitable for cultivation, and, in the case of eastern and southern Asia, current cropland areas even exceed these estimates considerably. South America, Sub-Saharan Africa, North America and Oceania, on the other hand, (areas of lower population density) have high cropland potential per inhabitant. Looking towards the future potential for cropland expansion, these estimates identify large areas with a potential for cultivation but which are currently not cropland, in South America and Sub-Saharan Africa.

However, large areas of these lands are currently forested, sustaining high values of biodiversity and carbon storage. The expansion of cropland in these areas, therefore, would involve significant drawbacks in terms of environmental burdens. In the UNEP land report (Bringezu *et al.*, 2014), a threshold of 0.20 ha/person was defined. Cropland area should be restricted to this level.

Figure 34

Land suitable for cereal cultivation versus cropland area in 2000 for 10 world regions



Legend: land suitable for cereal cultivation (left side, based on data from (Fischer *et al.*, 2001), categories very suitable and suitable for cereal cultivation with mixed levels of inputs) versus cropland area in 2000 (right side, based on data from (FAO, 2012)) for 10 world regions. The height of the bars represents per capita values, the width the number of people in a region. The area of each bar represents the absolute amounts.

Studies on virtual or embodied land

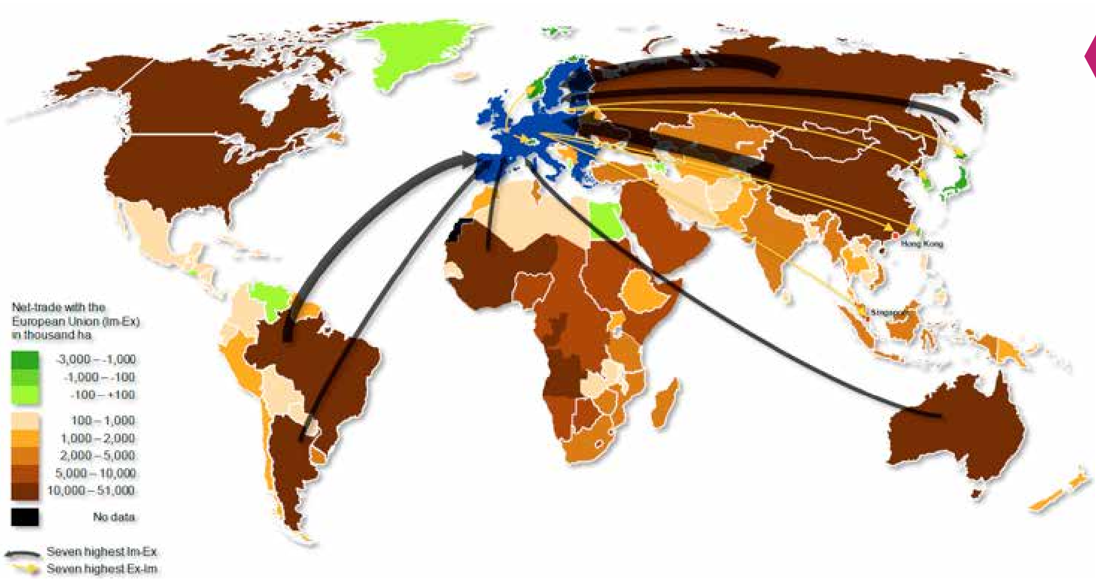
Recently, a number of studies based on IO models which estimate land demand embodied in consumption have been published (Costello *et al.*, 2011; Steen-Olsen *et al.*, 2012; Weinzettel *et al.*, 2013; Yu *et al.*, 2013). Costello *et al.* (2011) conclude that the US was a net importer of embodied land, especially forest area. Similar studies exist for the European Union; these studies establish that the cropland demand linked to this consumption is considerably larger than the EU's present cropland area.[28] An example of this is presented in Figure 36. While most of these studies give only a one-year snapshot, Kastner *et al.* (2014) recently produced a time series on trends in cropland embodied in the international trade of agricultural products for the period 1986 to 2009. They found that, while cropland used in direct domestic consumption remained almost stable at the global level in this period, cropland for export production increased by over 50 per cent or just below 100 Mha.

The use of input-output analysis, often through the adoption of MRIO models, has been suggested as an alternative to work based solely on biophysical trade and yield data. Mostly, such approaches use monetary IO tables. Hubacek and Giljum (2003), however, present an ecological footprint analysis based on physical IO tables. The practical use of linking trade to actual land-use is limited by the high level of sector aggregation (agriculture, forestry and fishing constitute a single sector in this study); the same limitation also holds true for many monetary IO studies. A recent commentary argues that, for embodied land, further in-depth investigations to explain or reconcile differences between IO-based results and results of biophysical approaches is needed, before clear, policy-relevant conclusions can be drawn (Kastner *et al.*, 2014).

28 Bringezu *et al.* (2012) argue that the EU's domestic cropland area was about 0.25 ha/cap. From 2000 to 2007 the croplands linked to domestic consumption exceeded 0.3 ha/cap. Van der Sleen (2009) shows that net imports into the EU were around 15 Mha for the period studied. Von Witzke and Noleppa (2010) estimate considerably larger net imports of embodied land (35 Mha in 2007/2008); their results reveal the dominance of oilseeds (above all soybeans) in these flows of embodied land. Using an IO approach, Lugschitz *et al.* (2011) also showed that Europe largely depends on overseas lands.

Figure 35

Trade balance of the EU in terms of embodied land



Source: (Lugschitz et al., 2011)

Meyfroidt and Lambin (2009) put land-use linked to international trade in the context of forest transitions (i.e. the change from net deforestation to net reforestation within a region or country) and show that Viet Nam's forest transition was partly driven by the displacement of land-use to other nations. Later, this work was expanded by conducting similar, comparative analyses for 12 nations (Meyfroidt *et al.*, 2010). They discovered displacement effects in many nations that have passed through a forest transition.

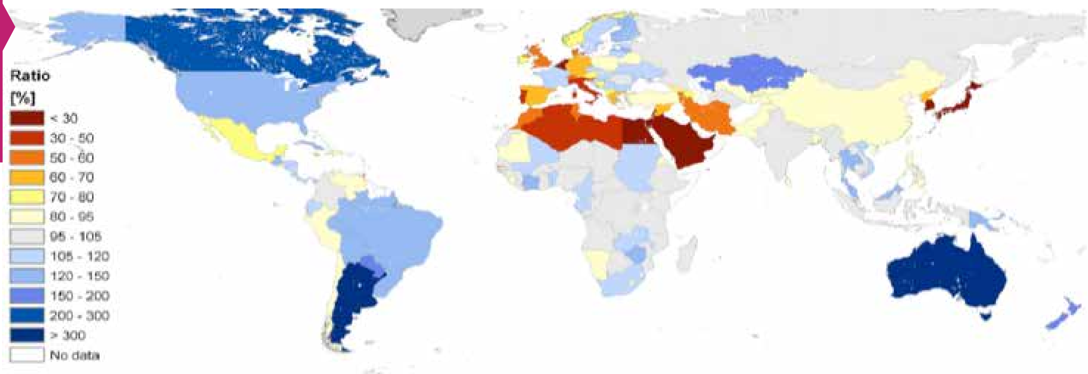
Embodied HANPP

Land represents a resource with highly differing qualities. As explained earlier, one hectare of fertile cropland can produce food for a large family, while the same area with low natural productivity can hardly produce any biomass output at all, unless massive, costly colonization measures are undertaken. This is important to consider when aggregating results into total hectares linked to the consumption of biomass products. HANPP (Human Appropriation of Net Primary Production) and its various sub-components represents a comprehensive set of indicators of land-use intensity, which measure how humans alter the biomass available in ecosystems through land-use practices. In addition to land, this section will also cover assessments of HANPP linked to trade (i.e. accounts of embodied HANPP).

There are a number of studies that explore the use of embodied HANPP in investigating land-use impacts linked to trade. Haberl *et al.* (2009) provide a conceptual framing for the approach. Erb *et al.* (2009) present a global account of HANPP linked to net trade between nations. They find sparsely populated regions to be the main net exporters and densely populated ones the main net importers, irrespective of development status. This is confirmed by Haberl *et al.* (2012), who use the data for a statistical analysis across 140 nations. The main result from the former study (Erb *et al.*, 2009) is presented in Figure 36: it shows, at national levels, the ratio between HANPP occurring on a nation's territory and the embodied HANPP linked to a nation's consumption of biomass products. While blue tones indicate net exports of embodied HANPP, red colours imply net imports of embodied HANPP and therefore dependency on foreign land resources. The map shows that the Americas and Oceania were the main suppliers of land-based products, while many European countries, as well as Japan and Korea, and countries in northern Africa and western Asia were importing considerable amounts of embodied HANPP.

Figure 36

Ratio between HANPP on a nation's territory and embodied HANPP linked to a nation's consumption



Source: (Erb et al., 2009)

Infobox 3

Ecological footprint

The ecological footprint (Kitzes *et al.*, 2008; Wackernagel and Rees, 1996) presents an aggregate indicator, aimed at translating human consumption levels into demand for biologically productive land, expressed through the common denominator 'global hectares'. The ecological footprint is typically calculated by translating the (apparent) consumption into 'global hectares', applying global average values for land productivities. A 'global hectare' therefore reflects the area that would be needed to produce a given product on land of global average productivity. Additionally, different types of land use receive different weightings, reflecting differences in average land quality (e.g. cropland vs. grassland). Besides land for biomass products, the ecological footprint also includes CO2 areas. This measure seeks to translate CO2 emissions from fossil fuel combustion on a territory or by a person into the land area that would be required to sequester these emissions. While these lands are also expressed in 'global hectares', they are hypothetical and do not actually exist. By comparing the calculated overall value (either global, national or per capita) to the available land resources (or 'biocapacity', also translated into 'global hectares'), the indicator provides easily communicable messages of (un) sustainability. An ecological footprint larger than the available 'biocapacity' is termed an ecological deficit or, at the global level, overshoot. At the global level, this overshoot is caused by the inclusion of the CO2 areas, as in the present indicator framework; such an overshoot cannot occur in the absence of fossil fuel use.

From this short methodological overview, it becomes clear that, while expressed in 'global hectares', an ecological footprint is not an indicator that assesses actual land use induced by consumption or trade activities, primarily because of the weighting processes, and the mixing of existing and hypothetical land areas. Rather, the ecological footprint is mainly a reflection of differences in consumption patterns and lifestyles. As clear links between resource flows and the physical land areas used for their provision are difficult to establish within the ecological footprint framework, we do not cover the vast literature on the subject comprehensively in this report.

Conclusions on biomass trade and upstream requirements

Biomass extraction is distributed unevenly around the globe – to a large extent due to different endowments of land suitable for agricultural production – and trade in biomass products is required as a balancing mechanism for supply and demand. High population density areas are characterized by low per capita biomass harvests and by small amounts of per capita land suitable for agricultural production. Areas of low population density, on the other hand, have large availability of potential agricultural land and harvest high amounts of biomass in per capita terms. Therefore, biomass trade flows from sparsely populated countries (North and South America, Oceania, the FSU and parts of Sub-Saharan Africa) to areas of high population density (Asia and Europe).

Biomass trade has grown at comparable rates to other material categories, but upstream requirements of biomass materials have grown faster than directly traded biomass. The faster growth in upstream requirements mainly results from the growing share of higher-processed biomass products in trade. Higher-processed products have, by definition, higher upstream material requirements, compared to goods at lower processing stages. For agricultural products, the growing share of animal products in the trade mix can serve as an example of this trend (Regmi, 2001).

At the global level, Asian and European countries are close to maximum productivity for their available land. Intensification is at a maximum and does not leave much space for further increases in productivity. These densely populated areas are depending on imports from other regions, i.e. regions of low population density. Latin America, North America, and some areas in Sub-Saharan Africa are focussed on high per capita biomass extraction, and thus make use not only of the availability of land but also of the high productivity of the available land area. In terms of future capacities, these regions have additional and productive land available for biomass harvest. However, expanded biomass production in these regions has resulted in the cutting down of forests, land degradation and ecosystem changes (Foley, 2005; Krausmann *et al.*, 2013; Lambin and Meyfroidt, 2011; UNCTAD, 2012; Zika and Erb, 2009). Moreover, high inefficiencies in harvest technologies have aggravated these effects (UNCTAD, 2012). In terms of future potential, increases in efficiencies can, to some degree, compensate for the environmental problems. However, increasing land degradation and loss of forest area can be expected.

4.2 Metals trade and upstream requirements

Metals play a central role in economic development. The ability to forge and use metals has enabled humans to construct more efficient tools and instruments for agriculture, construction and military purposes.

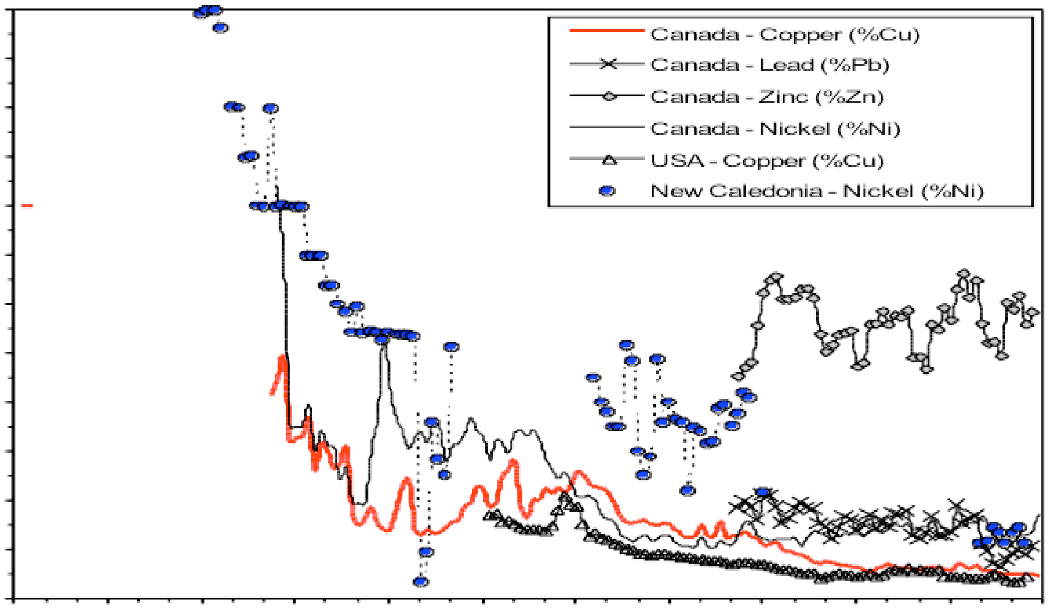
Until the nineteenth century, humans processed only a limited number of metals, such as copper, tin and iron. Today, however, almost every element in the periodic table is extracted and used on an industrial scale for producing specific materials and high-tech commodities. Out of the more than sixty different metals existing in nature, mass flows in human economies are made up of iron and manganese (used mainly for structural steels), aluminium (primarily required in transportation), lead (for use in batteries), and copper (essential for the transportation of power, and energy) (Graedel, 2010). With the exception of lead, these metals are used widely in mass applications such as infrastructure and buildings. According to Allwood and Cullen (2012), out of the more than 1 billion tons of steel produced every year, 42 per cent is used in buildings and 14 per cent in infrastructure, with a further 16 per cent being used in electrical and mechanical equipment and a further 12 per cent in cars, trucks and ships. Out of the 45 million tons of aluminium products produced every year, around 26 per cent is used in transportation equipment (cars, trucks and planes), 24 per cent in buildings, 20 per cent is required in industrial equipment and 13 per cent is used in packaging (Allwood and Cullen, 2012). Other metals, such as indium and platinum, are increasingly used in small or even microscopic amounts, especially in the electronics industry. Graedel (UNEP, 2010) concludes that hardly any chemical element can currently be eliminated from the list of those that are important to modern society and to cutting-edge technology.

Thus, metals are mainly a flow from extraction to processing and eventually to stocks, which are accumulated in societies for years, if not centuries. The history of economic development reflects countries' use of metals and the per capita stocks accumulation. Industrialized countries have naturally accumulated larger per capita stocks of various metals, compared to less developed countries (Graedel, 2010). Copper stock per capita, for example, is around four to ten times higher in developed countries than in less developed countries, while stainless steel stock is between five and twelve times higher, again in favour of developed countries.

Metals are a non-renewable material, each extraction reducing and depleting the respective deposit. Worsening ore grades partly reflect the current degree of depletion of accessible resources (Figure 38). Continuing metals extraction and depleting deposits means that more gross ore has to be broken out, with potential impacts on local and global ecosystems and with higher input requirements of energy, water and chemicals. Metal ores and metal products are highly diverse - both in terms of price per tons and in metal content per ton of gross ore.

Figure 37

The declining ore grades of metals



Source: (Mudd, 2010)

Although not a renewable resource like biomass, metals can be recycled and used several times. However, less than one-third of existing metals have an end-of-life recycling rate above 50 per cent, and thirty-four of these register a recycling rate below 1 per cent. Clearly, boosting recycling rates is still a global challenge (Graedel *et al.*, 2011).

The extraction and processing of metals contribute to a multitude of environmental problems. The recently published UNEP International Resource Panel Report on "Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles" (van der Voet *et al.*, 2013) provides a comprehensive synthesis of existing knowledge on the environmental impacts of metal use by humans.

The environmental problems caused by metals use depend, among other things, on the respective metal, the specific characteristics of the deposit, and the technologies of extraction and processing. Examples of environmental problems include:

- Removal of ecosystems and human settlements for the installation of mines and access roads to the mines
- Dust and noise pollution, as a result of open-pit mining operations such as blasting and haulage
- Damage resulting from crushing and grinding operations
- Disposal or release of toxic substances (if not used properly) and their impacts on local populations

- General contamination and overexploitation of soil and water reserves near the mines or processing locations.

Deposits of metals are geographically concentrated, in contrast to biomass resources. Even though a large variety of metals exist in the earth's crust everywhere on the globe, these sources are considered to be deposits only if extraction is economically viable. Economic viability, in turn, depends on several factors, such as concentration, accessibility, available technologies, by-products and price expectations. Thus, the geographical distribution of metal deposits is fixed from a geological point of view but is changing over time, in terms of accessibility, according to improvements in technology and exploration as well as through depletion of sources.

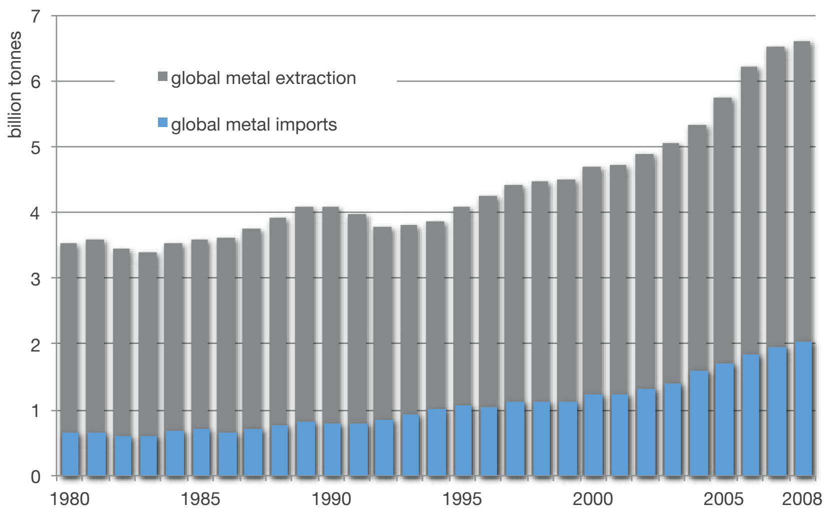
For different reasons and on the basis of current knowledge of deposits, some countries such as China and Australia are well endowed with various deposits, while other countries have found very few deposits to date. Commercial grades of some metals, such as copper, cobaltand tin, are concentrated among a handful of countries. In 2010, the three leading tin- producing countries were responsible for 78.4 per cent of global tin extraction and contained around 58 per cent of global reserves (BGR, 2012).

The uneven geographical distribution of deposits and their limited substitutability (considered impossible in some industries and applications) drive international trade in metals. Countries without sufficient domestic sources have to depend on imports of metals. Compared to biomass, where average import dependencies are low (the global average share of biomass imports in DMI was around 8 per cent in 2008), average global import dependencies for all metals is fairly high, with a 24 per cent imports share in DMI. When measured in raw material equivalents, this share rises to 62 per cent of imports (Wiedmann *et al.*, 2013).

Direct trade of metal goods

Global extraction of metals has increased by 87 per cent in the past three decades, from around 3.5 billion tons to 6.6 billion tons in 2008 (SERI, 2011, Figure 39). During the same period, trade in metals increased by 216 per cent, to 2.1 billion tons in 2008. According to MFA methodology, metals extraction includes gross ore (which also contains a large proportion of non-metallic minerals and rocks). Metal trade, on the other hand, includes only physically traded metallic commodities, which are predominantly processed ores and concentrates. Trade in metals also includes alloys and semi-products, made mainly out of metals, such as wires, tubes, rods and tailings, as well as metal-based goods such as cars or machinery.

Global metal extraction and trade, 1980–2010



Sources: Extraction: (SERI, 2011); trade: (Dittrich, 2012); note: trade as global imports.

Figure 38

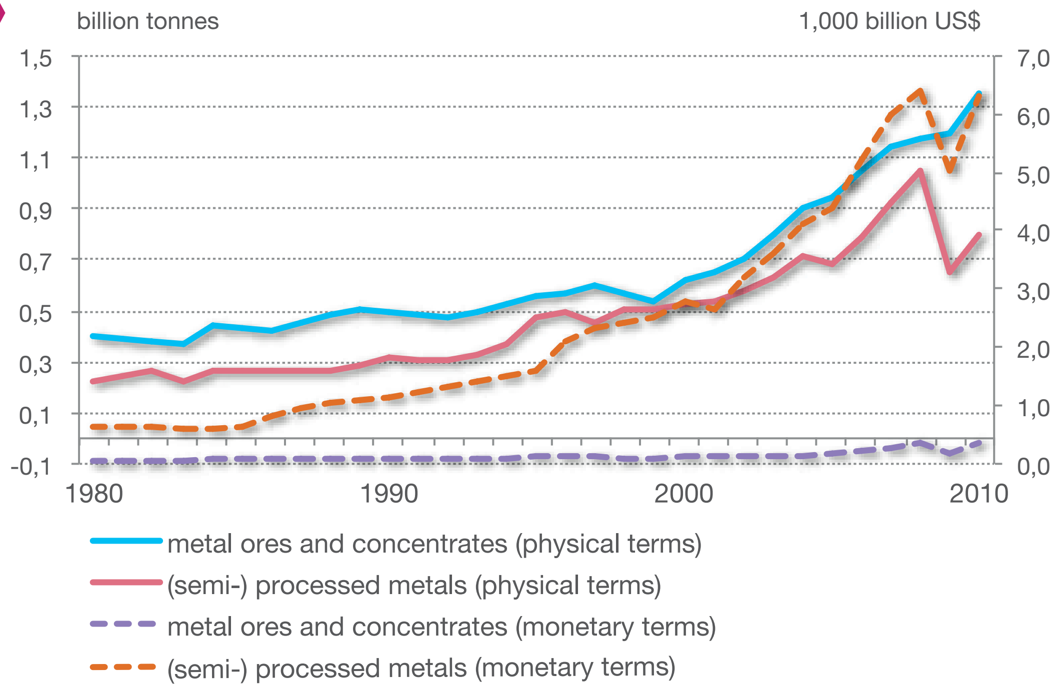
Trade in metals has been increasing faster than extraction rates (+224 per cent), especially since the turn of the millennium. Enlarged and more differentiated international production chains of metal goods are driving this rapid rise in trade. Trade in semi-manufactured and final products made out of metals has increased by 302 per cent during the past three decades, leading to multiple counting of the same material.

However, in nearly all the years observed, the weight of traded metal ores and concentrates exceeded the amount of traded (semi-) processed metals (Figure 40). The monetary value of processed metals exceeded the value of traded metal ores and concentrates during the same period. Metallic products follow the same weight to value relationship during their life cycle, as explained in the Introduction. Metals lose weight particularly during the first process of converting gross ore into concentrates, while the value per unit of weight rises.

In 2009, trade in processed metals decreased in monetary and physical terms, reflecting the global economic slump; however, metal ores and concentrates trade increased in terms of weight and dropped only slightly in value. The ongoing demand for raw materials in emerging economies, in particular China, was a contributing factor to the continued increase in trade.

Figure 39

Trade in metals by degree of processing in monetary and physical terms, 1980–2010

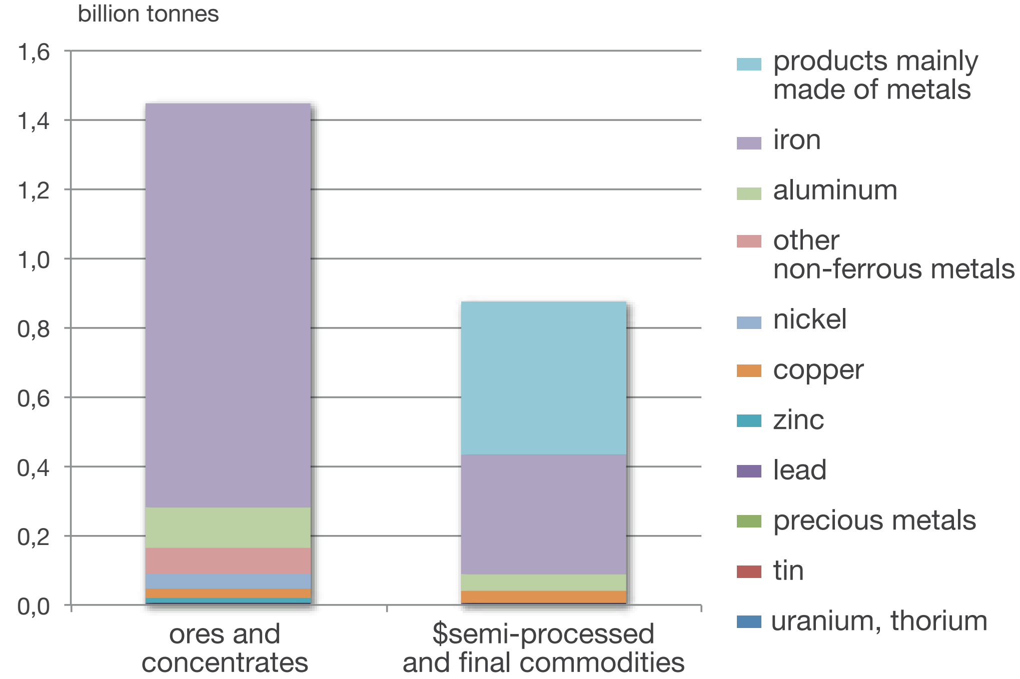


Source: Monetary terms: United Nations Comtrade; physical terms: (Dittrich, 2012). Note: trade measured in imports.

In 2010, around 1.4 billion tons of metals, in the form of raw materials and concentrates, and 0.8 billion tons of (semi-)processed and manufactured metal products were traded. Iron ores and concentrates held a share of around 83 per cent in traded raw metal ores and concentrates (Figure 41). Iron was followed by aluminium, nickel and copper.

Composition of traded metal goods by degree of processing, 2010

Figure 40

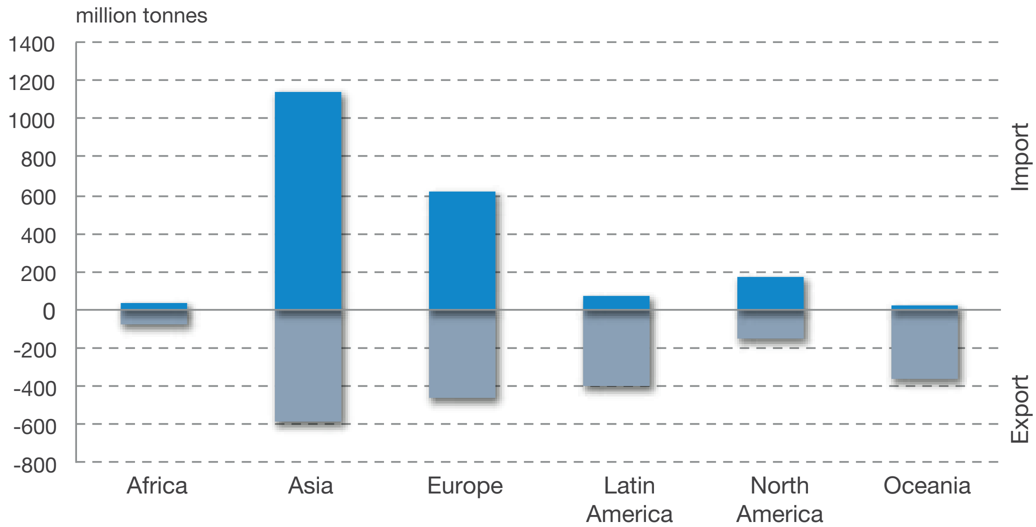


Source: (Dittrich, 2012).

Asian countries recorded the highest volume of trade in metals (imports plus exports), followed by European and Latin American countries (Figure 42). Australia (including Oceania) was the largest net supplier of metals, with 338 million tons in 2008, followed by Latin America and Africa, with 322 and 39 million tons, respectively. Asia was the dominant net importer, with 548 million tons, followed by Europe and North America, with 162 and 27 million tons, respectively.

Trade of metal goods by continent, 2008

Figure 41



Source: (Dittrich *et al.*, 2012)

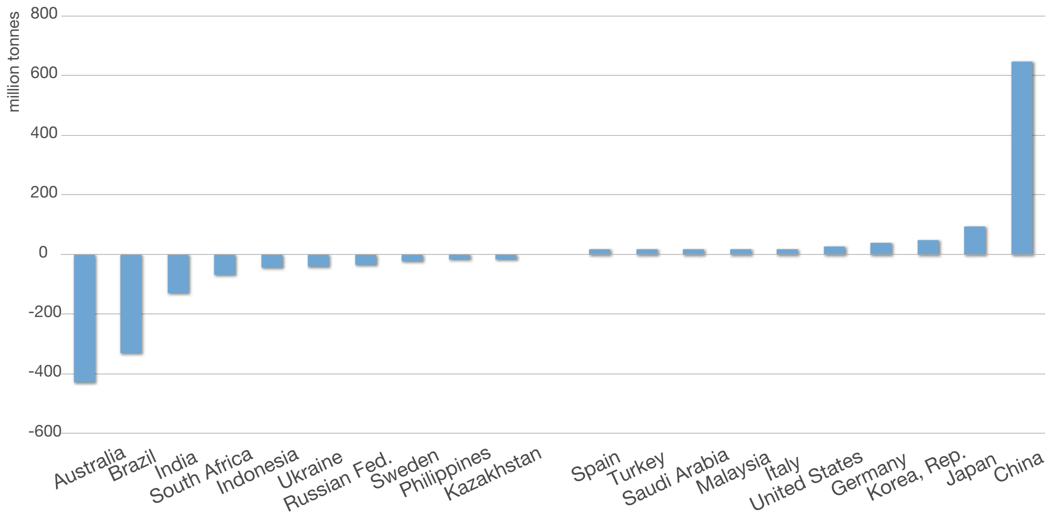
The geographical distribution of metals trade tracks to some extent the respective deposits, extraction rates and specific demands of industries in the different countries. All large global suppliers of metals are countries with large reserves (according to a World Bank estimate (2006), in which 10 metals[29] and minerals were considered) and high extraction rates of metals (SERI, 2011). Examples of metal- and mineral-rich countries with high extraction rates include Australia, Brazil, Chile, Indonesia, Russia, India and South Africa. Except for Chile, all of these countries are among the ten main global suppliers of metals.

29 Bauxite, copper, gold, iron ore, lead, nickel, phosphate, tin, silver and zinc

But not all countries with high reserves and extractions are supplying to the world market. China is the most prominent example of this: according to the World Bank (2006), it is the fourth richest country in metals and minerals and, according to SERI (2011), was the country with the highest absolute metal extraction in 2008, at around 1.2 billion tons. Despite this, China is currently the largest importer of metals.

Figure 42

Main net suppliers (10 countries) and main net importers of metals (10 countries) in the year 2010



Source: Dittrich, 2012

China is an extreme but typical example of metal-importing countries. Industrialized countries and emerging economies with medium reserves and extractions per capita are major metal importers. For example, the US ranks 32nd in metals wealth per capita (World Bank, 2006) and 31st in metals extraction (SERI, 2011), but it is in 4th place as a net importer (Dittrich, 2012). Japan ranks 62nd in metals wealth (World Bank, 2006) and 105th in per capita metals extraction (SERI, 2011), but is in 2nd place as a metals importer (Dittrich, 2012). China ranks 43rd in mineral wealth per capita and 42nd in metals extraction per capita (SERI, 2011; World Bank, 2006), but is the world's largest net importer of metals. Natural endowment is not the only factor determining metals extraction and trade. Environmental standards, public pressure and costs of extraction also contribute to the decision of countries to rely upon imports rather than domestic metal extraction.

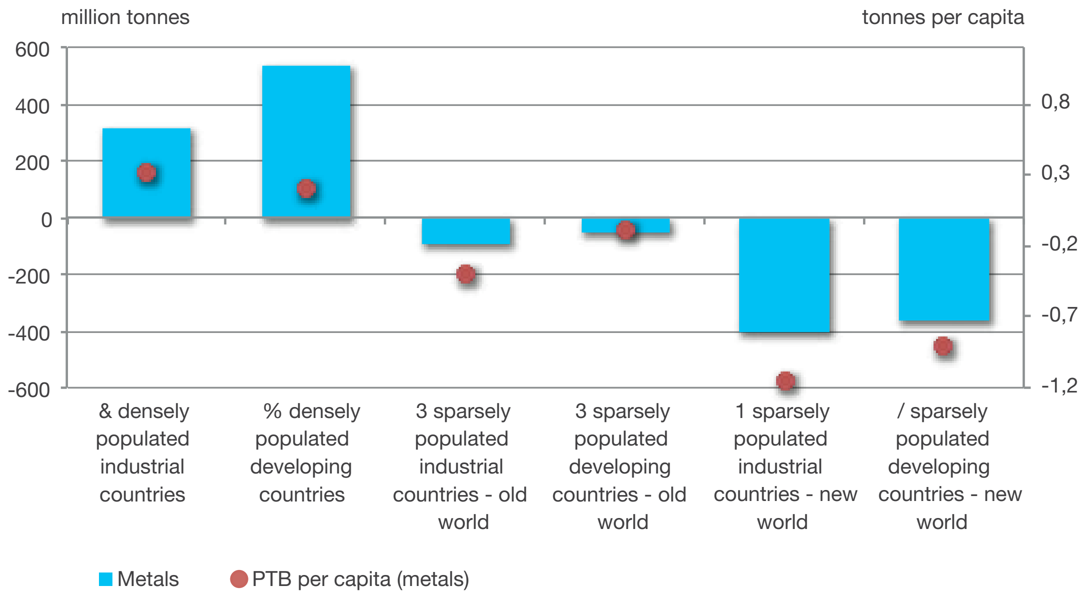
The number of both exporting and importing countries has increased in recent decades because several new countries have come into existence (e.g. countries from the former Soviet Union). Nevertheless, the relationship between the exporting and importing countries has remained constant: one exporting country as against around 3.4–3.8 importing countries, throughout the period observed.

As with other resources, densely populated industrial and developing countries are predominantly importers, while sparsely populated industrial and developing countries are largely exporters. 'New world' countries such as Australia and Latin America exhibit significantly higher values of per capita metal exports.

Physical trade in metals reflects the history of population settlement, exploitation and recent development trends linked to increasing material requirements that cannot be provided locally within reasonable economic, social and ecological limits.

Figure 43

Metal trade according to population density and development status



Sources: (Dittrich, 2012; World Bank, 2012); grouping according to (Krausmann *et al.*, 2008)

The high volume of accumulated metal stocks in industrialized countries, in the form of infrastructure and manufactured goods, is providing an important future source for metals, generally referred to as 'urban mining'. The term describes the recycling of secondary resources that are temporarily accumulated in societal in-use stocks above ground (so-called 'urban mines'). Some emerging economies, such as China, South Korea and Singapore, are also rapidly accumulating stocks of metals.

The reuse and recycling of human stocks is already a part of the international trade in metals. The proportion of waste and scrap in metals trade increased from 4.3 per cent in 1980 to 6.8 per cent in 2010. Examples include trade in transportation equipment and in recycled machines.

Upstream requirements of traded metals

Trade in metals supports the global effort for higher resource efficiency by optimizing the distribution of supplier countries and consumer countries of metals. In a hypothetical economy without trade, each country would have to extract the required metals locally – from nature or from human stocks. This would mean immense technological efforts and costs, as well as severe environmental impacts in countries with a high demand but a low endowment of deposits.

Theoretically, trade allows metals to be extracted and processed in locations with the least-induced environmental impacts during the production processes. A comparison of the environmental impacts of the extraction and processing of metals in different countries has not yet been undertaken, to our knowledge, and is certainly not a simple task. Currently, required upstream resources for extraction and processing, in particular energy, materials and water, are used as proxies to discuss the environmental impacts of metals trade. The results will be presented in the following section.

Upstream material requirements of traded metals (RME accounts)

A comparison of extraction and trade of metals does not reveal much, because of the huge (and variable) difference in volume between gross ore (the measure for extraction) and concentrates or further-processed products in trade. However, comparing extraction and the raw material equivalents of traded metallic products yields information on the share of metals extraction directly or indirectly redistributed by international trade.

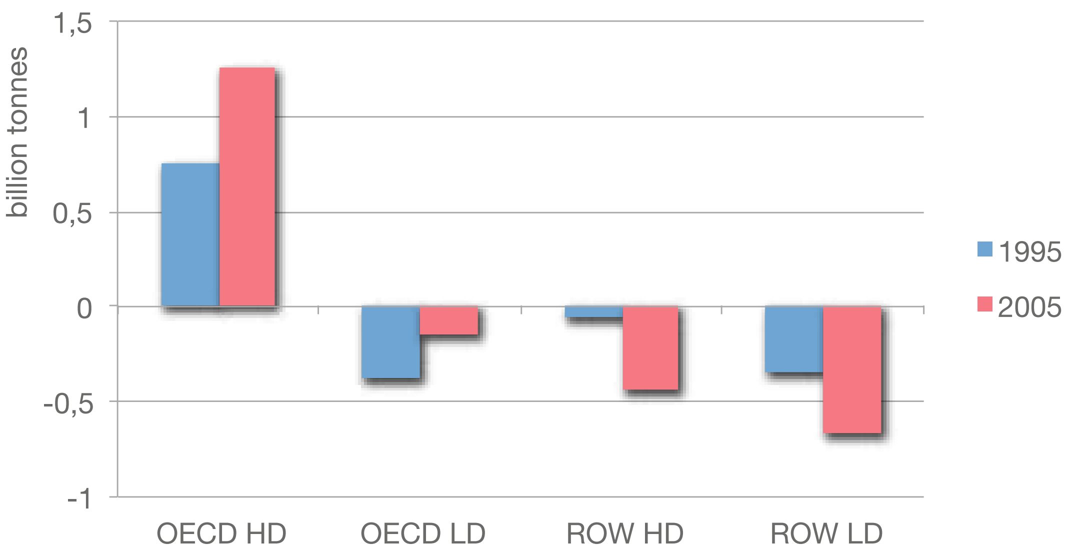
Global level data on raw material equivalents of traded metals have been published recently. The first results of the GRAM-model[30] show that, while, in 1995, 26.9 per cent of global metals and industrial mineral extraction was traded directly or indirectly, in 2005, this figure rose to 37.6 per cent (Bruckner *et al.*, 2012). Wiedmann *et al.* (2013) calculated that 62 per cent of metals extraction was linked to trade in 2008. Thus, global metals consumption is increasingly met through imports.

Bruckner *et al.* (2012) found that densely populated OECD countries net-imported, directly or indirectly, 1.2 billion tons of metals and industrial minerals extracted in foreign countries for domestic final demand, whereas sparsely populated OECD countries, as well as high and low population density countries from non-OECD countries, net-exported (directly and indirectly) metals and industrial minerals in 2005 (Figure 45; Bruckner et al, 2012). Compared with 1995, key changes occurred in the densely populated group of non-OECD (rest of the world) countries, where net exports, measured as raw material trade balance (RTB), increased by 780 per cent. The countries increased exports of non-renewable resources to match local demand for commodities. In contrast, sparsely populated OECD countries decreased net exports of metals by 60 per cent.

30 The GRAM-model sums up metals and industrial minerals as well as directly traded metals and upstream flows.

Figure 44

RTB of metals and industrial minerals by country group, 1995 and 2005



Source: Own figure based on (Bruckner *et al.*, 2012); HD: high population density, LD: low population density, ROW: rest of the world

Muñoz *et al.* (2009) used environmentally extended input-output tables to calculate raw material equivalents in five Latin American countries (Brazil, Chile, Colombia, Ecuador, and Mexico). This effort is the first of its kind. The calculations reveal that Chile displayed the largest difference between direct physical trade balances and raw material equivalent trade balances. An average ton of Chile's exports, one of the world's major copper suppliers, required around 25 tons of upstream materials imports in 2003.

Upstream material requirements of traded metals (LCA accounts)

In contrast to the above-mentioned approach, which allocates extraction to final demand, the life cycle approach focuses on the upstream materials required to produce the traded products. For example, in the LCA approach, upstream material requirements of traded metals include the fossil fuels used during extraction, processing and transport. Many LCA-based assessments of trade (for example, Dittrich *et al.*, 2012) also include unused extraction, e.g. the removal of the top layer of the ground and vegetation before a mine is installed.

Dittrich *et al.* (2012) estimated that traded metals have accounted for around 50 per cent of the global upstream material requirements of all traded goods since 1962. According to Dittrich *et al.* (2012), iron (as ore, concentrates and steel) accounts for the highest share in associated indirect flows. An example of an extreme relation is copper, which accounted for only 0.5 per cent of direct trade but for 10 per cent of all indirect (i.e. upstream) trade flows. According to the study, the ten countries with the highest upstream (waste) materials are sparsely populated, while ten countries that import metal commodities with the highest upstream material requirements are densely populated.

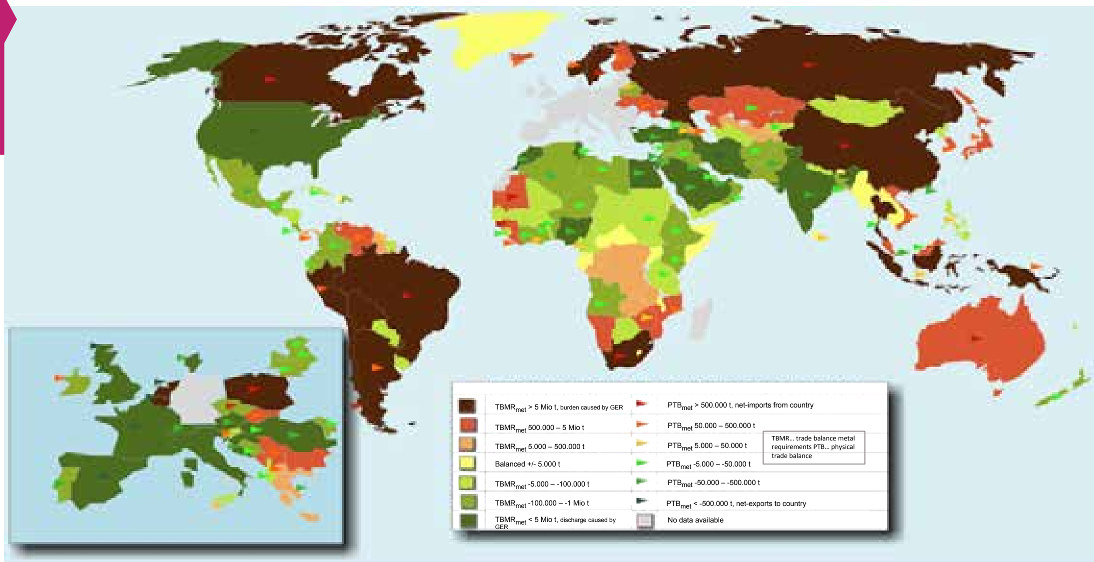
There are several studies on metals in a broader sense (e.g. European Commission, DG Enterprise, 2014; Moss *et al.*, 2013). From a material perspective, there are a number of studies that analyse material requirements at regional levels, for the European Union, for example, as one of the main importers of metals during past decades. The first such study was carried out by Schütz *et al.* (2004). The authors observed the general trend of an increase in the material requirements of the European Union between 1976 and 2000, in particular in processing industries and through increased imports of metals as raw materials and semi-manufactured goods. In 2000, nearly two-thirds of the European Union's material requirements could be attributed to imported ores from developing countries. The dominance of metals trade in the European Union's material requirements from abroad and the increase in requirements during past decades have been confirmed by subsequent studies (e.g. Schoer et al., 2012).

Some studies investigate metals trade as part of trade in selected countries. For example, the German Environmental Agency's (Dittrich *et al.*, 2013; UBA, 2008) analysis of upstream materials in Germany's trade flows reveals that metals trade is responsible for the highest amounts of upstream requirements. An average ton of imported metal was linked to around 11 tons of upstream material requirements in 2008; in the average of all traded goods, each ton of import was linked to 4.3 tons (2008). The ratio has increased over past decades: in 1980, each imported ton of metal had only been linked to 8 tons per imported ton of metal. The increase reflects several trends: generally worsening ore grades over the decades, but also a trend towards importing more metals with particularly high upstream material requirements, such as copper.

The material requirements of many European countries' exports are also dominated by traded metals, although these countries export metals as further-processed or final goods. Aachener Stiftung Kathy Beys and Dittrich (2010) calculated that, in 2005, Germany tended to have a negative direct and indirect metal trade balance with countries to which it was exporting metal products. On the other hand, Germany is (net) importing more raw and semi-processed metals with high (net) upstream requirements from 59 countries, in particular from South America (iron and copper), Scandinavian countries (alumina), South Africa (iron ores), Canada (iron ores and titanium), China (tin, iron alloys and electronic appliances) and Australia (iron ores).

Figure 45

Germany's direct trade in metals and the material requirements of Germany's metal trade by country, 2005



Source: (Aachener Stiftung Kathy Beys and Dittrich, 2010)

Germany is a good example of how trade 'redistributes' the environmental burden in terms of upstream materials: in extracting countries, such as Brazil or Chile, the highest amounts of upstream materials remain as wastes and emissions. In processing countries, like Germany, metals are further refined and other material inputs, including energy carriers, are added; afterwards, the metals are either consumed domestically or exported as high-quality final goods, such as cars or machines. Countries which are neither extracting nor processing metals but only importing them, in the form of final goods, have positive trade balances of direct and indirect metal trade, implying that their imports are linked to high material requirements abroad. Examples include islands without domestic mines and processing industries, and countries such as Saudi Arabia and Kenya, where no metals sources have been discovered so far, or which do not have processing industries but nonetheless require imports of cars, machines, weapons and appliances.

As explained earlier, LCA-based approaches to upstream requirements offer a crystallized view of ore grades and the degree of concentration of traded metals. The lower the ore grades and the more advanced the processing of the metal, the higher the material requirement for the traded metal. Furthermore, the inclusion of unused extraction also reflects human encroachment on the top layer of soil and on ecosystems during the construction and operation of the mine. LCA coefficients may also comprise differences in technology and energy sources.

The main challenge presented by the LCA approach is the huge number of specific coefficients it provides for different mines across all locations and countries at all times, for different technologies and different additional inputs. However, most available studies are still based on country or global averages for certain metals and processing steps.

Upstream water requirements of traded metals

Water is an increasingly sensitive resource in many mining countries, as mining operations need it in substantial amounts, and this can result in major impacts on surface and groundwater resources. Even though a comprehensive study analysing upstream water requirements of traded metals is currently unavailable, a compilation of the links between mining in general and water requirements exists (Mudd, 2008). As many extracted metals are for export, this compilation may offer some insights into upstream water requirements of metals trade.

Many mining companies report annually on their sustainability performance; for example, within the framework of the Global Reporting Initiative (GRI),[31] most companies address water requirements, albeit in varying detail. Mudd (2008) analysed water requirements on the basis of the reports provided by mining industries in GRI. He observed that the water requirements of metal commodities vary significantly, both between and within types of metals. Gold clearly has the highest water requirements, with an average of 716,000 litres per kg gold, followed closely by platinum. Although several factors, such as mine type, ore mineralogy and mill configuration influence water requirements, declining ore grades of base metals result in higher upstream water requirements per unit concentrate.

Emissions linked to metals

Although this report does not focus on the environmental impacts of traded goods, it is important to emphasize that traded metals and metallic goods are linked to high amounts of emissions. Emissions in this context imply emissions of metals into the air, soil or water and emissions of further substances linked to the mining, refining, processing and trading of metals and metallic goods. UNEP IRP (2013) reports that emissions of metals into the environment (excluding landfill) have been estimated to be roughly of the same order of magnitude as natural sources (e.g. volcanic sources or weathering). Emissions of further substances relate to energy requirements during the mining, refining, processing and trading (particularly transporting) of metals and metallic goods. Energy requirements vary greatly among different metals and metallic goods. For instance, the production of metal from scrap material or secondary production generally requires much less energy than primary production, owing to the fewer steps involved. One of the most critical emissions linked to metals is sulphur dioxide, which occurs during the smelting of metal sulphide concentrates. Sulphur dioxide reacts with atmospheric water vapour to form sulphuric acid or 'acid rain'. Other significant emissions include arsenic dust in gold mining, which has a direct impact on human health. A detailed overview of emissions and impacts linked to metals use by humans is published in the UNEP IRP report Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles (van der Voet *et al.*, 2013).

Conclusions on metals trade and upstream requirements

Despite the high volume of international trade in metals, which supports the allocation of efficient extraction to countries with economic and resource availability advantages, the coincidence between economic efficiency and environmental and resource efficiency is not clearly established. Extraction costs depend on certain environmental factors, such as ore grades, water and energy costs or remoteness of the area, but also on environmental regulations, such as taxes, emission caps, regulations concerning health risks, etc. Technological know-how, wage levels, transport infrastructure and regional energy costs may outweigh the environmental component in extraction costs. Hence, for the purpose of environmental and resource efficiency, it is desirable that environmental costs be internalised in extraction costs.

Trade in metals reflects human settlement patterns, in that densely populated countries with an early industrialization history now depend on imports to satisfy a high domestic demand for metals. Countries with large (known) deposits and high extraction activity are naturally the dominant exporters, while industrialized countries or emerging economies with low to

31 For further information about the Global Reporting Initiative, see: www.globalreporting.org

medium, known metal deposits per capita are the dominant importers.

The global trend of declining ore grades is significant, as the quality of ore grades determines upstream requirements such as material, energy and water. Hence, the environmental burden associated with metals use and trade can be expected to increase, given the larger upstream requirements linked to lower-quality ore grades.

Recent research confirms that the upstream requirements of metals trade are on the rise, reflecting a change in the physical flows of traded metals. Trends point to a declining share of iron and an increasing share of copper and precious metals, which are associated with high upstream requirements. The different calculation methods for upstream resource requirements – LCA, IO models and hybrid approaches combining the two –, present widely diverging results that do not allow firm conclusions to be drawn (e.g. Schoer *et al.*, 2013).

Given the substantial environmental burden on extracting countries, international trade offers a certain degree of economic and environmental relief. Nevertheless, the environmental burden is being borne mainly by less populous countries in the North and South, to satisfy the high consumption demand in populous countries.

Infobox 4

Illustrative case study: Platinum

Platinum is a very rare metal. According to Earnshaw *et al.* (1997), its average abundance in the Earth's crust is 0.005 grams per metric ton, which is slightly higher than gold. In fact, economically recoverable concentrations of platinum are particularly uncommon, and much rarer than gold deposits. This explains why, in 2010, gold production exceeded platinum production by nearly 14 times. Platinum is primarily used in auto catalysts (41 per cent of demand, 101 metric tons in 2011), jewellery (30 per cent, 74 tons) and for investment purposes (6 per cent, 16 tons, Johnson and Mathey, 2012).

Canada, Russia, South Africa, the US and Zimbabwe contain the world's prominent deposits of platinum. The average grade of platinum ores is 2 to 3 g Pt per ton. Many deposits contain other metals as by-products, such as copper, nickel, gold and other platinum group metals. Platinum is also a by-product in certain chromite and nickel deposits.

From 1975 to2011, the compound annual growth rate of platinum production was 2.5 per cent, while the auto catalysts market grew much faster, at 5.9 per cent, following the widespread development of legislation to control car emissions. Auto catalysts are the fastest growing platinum-consuming market, a phenomen that has high environmental relevance. In 2011, the total platinum demand was 251.8 metric tons, of which 25 per cent was met through recycling. Recycling of platinum from end-of-life automobile catalytic converters is growing at a particularly fast rate: in 2011, 42 per cent of the required platinum for auto catalysts production was from secondary, recycled sources. Platinum can be recycled indefinitely from many of its end-uses. One of the adverse impacts of platinum from catalytic converters is its leakage into the environment, particularly into road dust, (Farago *et al.*, 1998), and from there into the blood and urine of road workers.

Platinum has many important applications in green technologies. In catalytic converters of automobiles, platinum acts as an oxidant for harmful CO and residual hydrocarbons, to produce less harmful CO2 emissions. Its use is particularly important and fast-growing in the exhaust catalysis of heavy-duty diesel engines. Several other environmentally important uses for platinum include fuel cell catalysis (e.g. Angerer *et al.*, 2009; Sharifi *et al.*, 2012), and gasoline production, improving efficiency in the use of crude oil, which is a non-renewable resource.

Production and trade

Primary platinum production (from mining) is geographically highly concentrated: South Africa (Bushveld Complex) accounts for 75 per cent of the production, Russia's Noril'sk region produces 13 per cent; Canada (Sudbury Complex, Ontario), the US (Stillwater Complex, Montana) and Zimbabwe (the Great Dyke) produce minor quantities. South Africa exported 96.9 of the 151 tons it produced in

2011. According to the data recorded in the United Nations Comtrade database, in 2011, South African platinum exports were mainly directed to the United Kingdom (33.3 tons, 34 per cent of exports), Japan (20.8 tons, 21 per cent of exports), USA (15.7 tons, 16 per cent of exports), Germany (11.7 tons, 12 per cent of exports) and Switzerland (9.6 tons, 10 per cent of exports).

All the countries mentioned above are home to companies engaged in one or several of the market segments. There is also significant platinum trade among countries with no platinum-mine production. Switzerland, for instance, home to some of the world's largest trading houses, exported about 60 tons of platinum in 2011, mainly to Hong Kong SRA China, the United Kingdom, China, Japan and Germany, plus smaller quantities to Canada, Belgium and France. At the same time, Switzerland imported 54.4 tons from several countries, of which only South Africa and the US were platinum-mine producers.

Although global in nature, the industry is dominated by a handful of companies engaged in platinum mining and metallurgical activities. The concentration of producing companies is almost as high as the geographic concentration of platinum mine locs: according to the commercial Raw Materials database,[32] in 2011, the five main producers controlled 81 per cent of all global production. If this list had been extended to the top ten companies, 93 per cent of global production would have been covered.

Refining for high purity is pursued by different companies, some of which also recycle platinum from end-of-life products like catalytic converters or old jewellery. Quite a number of these companies are also active in the production of platinum-containing products, such as catalysts or chemicals. The market leaders are located mainly in Asia, Europe and North America.

Environmental issues that may arise in relation to the platinum industry

The platinum industry is increasing its efforts towards establishing transparency in the environmental and social components of its operations, using specific guidelines developed by the Global Reporting Initiative. Forty-eight per cent of the world's platinum production in 2011 came from companies reporting their sustainability performance in line with GRI guidelines, 37 per cent of the global production came from companies having met GRI's highest compliance – 'A+ level' requirements –, which involves external, independent reviews of reports.

Platinum-mining activities generate a large amount of waste, owing to low grades of ores. Mudd and Glaister (2009) compiled energy and water use data available from GRI-compliant companies, which mine primarily at the Bushveld complex in South Africa. Key issues include energy and water use, dust, water contamination, CO2 and solid waste emissions. Data vary from one mine to another, since grades, depth and efficiency of ore recovery vary. A detailed inventory of the resource uses and emissions related to the production of platinum-group metals is available from the ecoinvent 2.0 life cycle inventories of metals (Classen *et al.*, 2009).

For every kilogram of platinum group metal (PGM) produced, energy requirements (essentially from coal) are 100 to 255 GJ (average 175 GJ, compared to 143 GJ for gold), 214 to 1612 m3 water (essentially fossil ground water), waste generation and GHG emissions ranging from 24,800 to 78300 t CO2/ ton PGM (average 39,400 t CO2/kg PGM). In accordance with ISO 14064-1, Anglo-American Platinum, the world's largest primary platinum producer, reports a total 2011 CO2 emission of 40,750 t CO2 per ton of precious metal produced (owing to the nature of its ores, the company co-produces platinum, palladium and rhodium, as well as gold). This figure is higher than the 35,000 t CO2 eq. per ton of produced platinum group metal estimated by Saurat and Bringezu (2008), who published a detailed platinum group metal material flow analysis, focusing on Europe. The example of positive changes in SO_2 emissions presented below shows the importance of a periodical revision (about every 10 years) of such analysis, owing to rapid changes in processing technologies, voluntary initiatives and regulatory frameworks, all of which have a positive impact on environmental performances.

Another source of harmful emissions is the smelting of sulfide ores, which generates large amounts of sulphur dioxide (SO2). In recent years, this has been mitigated through the recovery of SO_2, which is

32 Website: www.rmg.se

a resource in the production of sulphuric acid.[33] Hundermark *et al.* (2011) report a nearly 90 per cent reduction in SO2 emissions from Anglo-American Platinum's main complex, the Waterval smelter, from about 180 tons per day in 2003 to about 20 tons per day in 2012, thanks to intensive modernization in various key components of the smelting process. The current SO_2 emissions per ton of precious metal produced by Anglo-American Platinum are 127 tons SO2 per ton of metal.[34]

Emissions vary among platinum producers. There are three main streams of waste material related to platinum mines: waste rock, ore processing tailings (the unused part of the ore) and smelter slags. Data on waste rock are unavailable. Underground mining usually generates much less waste rock than open-pit mining, except for ore dilution resulting in barren rock, as the ore-bearing layer is less than one metre thick in most of the Bushveld mines. Almost 96-98 per cent of the ore becomes tailings, with low acid drainage potential. These tailings are disposed in tailing ponds that also store smelter slags. Backfilling of old underground excavations with tailings and some cement is only pursued by Northam Platinum in South Africa, an integrated PGM producer which operates the deepest mine and therefore is likely to use backfilling to improve the geotechnical stability of deep operations. Other environmental impacts include the release of arsenic from flotation tailings and/or metallurgical activities, as arsenic is a by-product of certain platinum ores. Technological developments in recovery of platinum from sulfidic ores through bioleaching are likely to contribute to a significant reduction in emissions from future platinum production.

(Information supplied by Patrice Christmann, BRGM France)

33 Sulphuric acid is economically important for several industrial production processes, including the production of phosphoric acid from phosphate rock, which is a critical step in fertilizer production.

34 Anglo-American Platinum is a mining and metals company that provides externally audited economic, environmental and social data on its operations in compliance with the Mining Industry Supplement of the Global Reporting Initiative guidelines.

4.3 Trade in fossil fuels and upstream requirements

The ability to transition from an agrarian society to a modern industrial society is determined by the ability to access abundant, cheap and concentrated sources of energy. Exploiting stocks of fossil fuels has helped societies overcome the strict limits to growth from having to rely on energy supplied b biomass harvests (Krausmann *et al.*, 2008). The availability of abundant and cheap energy resources that appeared in a concentrated fashion and were easy to transport underpinned industrialization and urbanization, and generated new levels of wealth and consumption in the industrial world. The sustenance of an industrialized society requires increasingly high levels of energy input. But the transition comes at an environmental cost, that of rising carbon emissions and accelerated climate change caused by the widespread use of fossil energy for heating, cooling, transport and most major industrial processes. Fossil fuels are still the main energy source, and the ability to access them is vital to any modern society until it makes a full transition to renewable sources. Substantial government subsidies for fossil fuel extraction, power generation and distribution have artificially lowered costs of fossil energy carriers and supported the energy regime globally.

Like many other natural resources, the geographical distribution of coal, natural gas and petroleum is uneven, with some individual countries accounting for large fractions of the global natural endowment. This is especially the case when the quality of deposits and the ease of exploitation are taken into account, and the overarching concept of energy return on energy invested (EROEI) comes into play. Fossil fuel endowment is not related to population density, thus large sources of supply are often geographically removed from the major centres of consumption.[35] All of these considerations explain why international trade in fossil fuels is such a large and strategically important business. Some major economies would not have industrialized without access to external supplies of fossil fuels, which has proved an alternative to colonialism/war in securing these supplies. Indeed, threats to continuity in trade of fossil fuels have been significant contributors to both the outbreak and the course of several wars since at least the 1940s.

In short, international trade in fossil fuels is, under the current global system, fundamental to overcoming mismatches between sources of supply and centres of demand for one of the most important requirements of modern, affluent societies.

The dynamics of trade in fossil fuels

The use of fossil fuels – coal, petroleum and natural gas – underpins modern industrial modes of production and consumption. The global extraction of fossil fuels has grown by 1.9 per cent CAGR (compounding annual growth rate) since 1970. Growth in the extraction and use of fossil fuels has exceeded population growth of 1.6 per cent in the same period. Hence, per capita fossil fuel use has grown by 0.3 per cent per annum. Over the same period, global GDP has grown by 3.3 per cent per annum. This indicates that while economic output was still strongly coupled to the use of fossil fuels in absolute terms (i.e. both continued to increase), they were decoupled in relative terms, since the fossil fuel input required to produce each unit of economic output fell by 1.4 per cent per year.

In many countries, the exploration, extraction and consumption of fossil fuels receives either direct government subsidies or tax concessions.

Direct subsidies are perhaps the easiest and (methodologically) the least controversial support measure to quantify. An International Energy Agency report (2011a) on energy subsidies showed that fossil fuels support from OECD countries was dominated by petroleum (54 per cent), of which consumers received 67 per cent support and producers 22 per cent. The remaining 11 per cent was given to 'General Services Support'. Another analysis by the IEA (2011a) shows that, at the global level, fossil fuel consumption subsidies are dominated by those given by major oil exporters to their local consumers, with oil importers typically accounting for less than 25 per cent of the global total. The level of subsidies in any given year is highly volatile, varying in accordance with fossil fuel prices; for example, global consumption subsidies of more than $550 billion in 2008 decreased to around $300 billion in 2009. Some problematic aspects of consumer subsidies highlighted in the IEA (2011a) analysis included:

- Encouragement of wasteful consumption
- Distortion of markets and creation of barriers to clean energy investment
- Dampening of global demand responsiveness to high prices
- Increase in CO2 emissions (a direct result of increased fossil fuel consumption)
- Acceleration of the decline of exports (for fossil fuel exporters)
- Drain on state budgets (for fossil fuel importers)
- Threats to energy security (by increasing imports)

While fossil fuel consumption subsidies are often linked to poverty alleviation strategies, there is a considerable amount of literature (e.g. IEA (2011a), World Bank (2014a)) which asserts that it is an inefficient method of achieving the desired objectives.The OECD states that reforming and eliminating financial support for the consumption or production of fossil fuels could contribute to achieving economic and fiscal objectives and would help to mitigate environmental problems

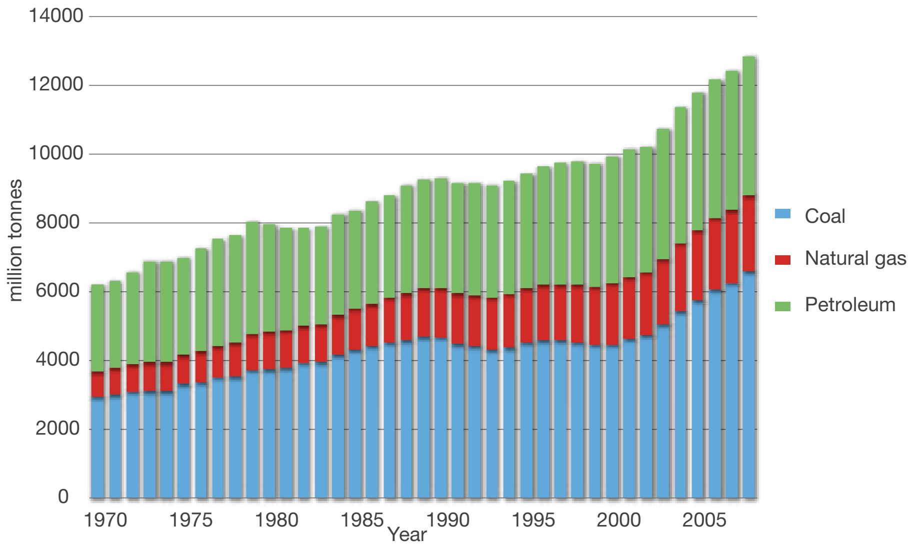
35 Historically, this was not always so: originally, the United Kingdom was by far both the largest producer and the largest consumer of coal, and this enabled it to build up an empire (Schandl and Schulz, 2002). Similarly, the United States of America was, for much of the 20th century, by far the largest producer of petroleum and the largest consumer, and this allowed it to build up its economic dominance. From the 1970s onwards, the US became increasingly dependent on imports of crude oil (Gierlinger and Krausmann, 2012), until recent years, when this trend was reversed (see U.S. Energy Information Administration (EIA), 2013).

such as climate change (IEA, 2011b; IEA *et al.*, 2011; OECD, 2012; World Bank, 2014b).

By 2008, coal accounted for almost half of the world's fossil fuel extraction in total tonnage terms. As one of the top three fossil energy carriers, its consumption grew by 2.1 per year on average (and faster during the stagnation of petroleum extraction in the last decade). Consumption of natural gas grew by 2.9 per cent per annum, while petroleum consumption witnessed a gradual growth rate of 1.2 per cent per annum (and hardly grew at all in the last decade). Coal's dominance comes from its central role in the energy transition of developing countries. China and India are leading examples of coal consumers, where it is the dominant fuel used for electricity generation. The relatively subdued growth in petroleum consumption and its decline relative to other fossil fuels has occurred despite the rapid growth in global transport and mobility requirements, and the rapid expansion of private car fleets (see Figure 46).

Figure 46

Global extraction of fossil fuels, million tons, 1970–2008



Source: CSIRO Global Material Flow Database

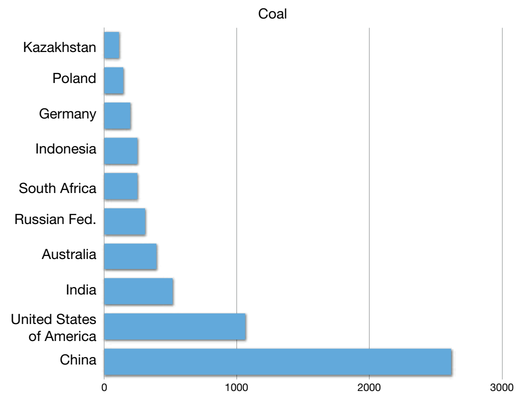
Another contributing factor to the dominance of coal as an energy carrier is the narrowness of the geographic mismatch between supply and demand. Nearly 90 per cent of all coal production in 2008 occurred in only 10 countries, with China, India and the US accounting for 64 per cent of that production. As the three most populous nations, they are also the main centres of demand for the electricity produced from coal (see Figure 47). This close matching of population and supply can in part be explained by the fact that low quality coal deposits can be cost competitive with high quality deposits in electricity generation, its main application. The ability to site a power station close to a coal deposit, and "ship out" only the final, upgraded product (electricity) can overcome many of the disadvantages that usually accompany using a lower grade resource, such as high transport costs.

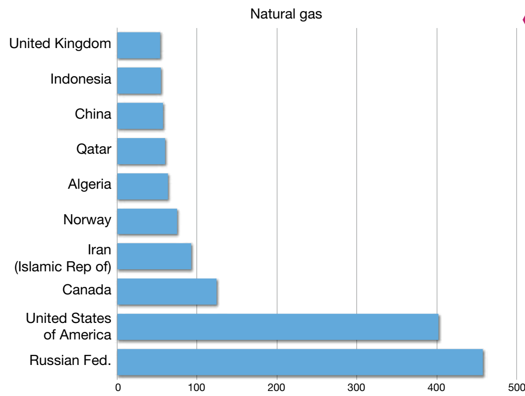
In the case of natural gas, production is less concentrated among the major producers, with the ten largest accounting for only 65 per cent of the global total in 2008, and the top three for just 44 per cent. However, among the top three natural gas producers (the Russian Federation, the United States and Canada), only the United States is among the most populous nations. This can be explained, in large part, in terms of the nexus between high local demand (driven by a large population) and high local extraction rates; the commodity becomes much weaker and more tradable over longer distances (resulting in a higher unit value, e.g. liquefied natural gas (LNG) versus poorer quality coals).

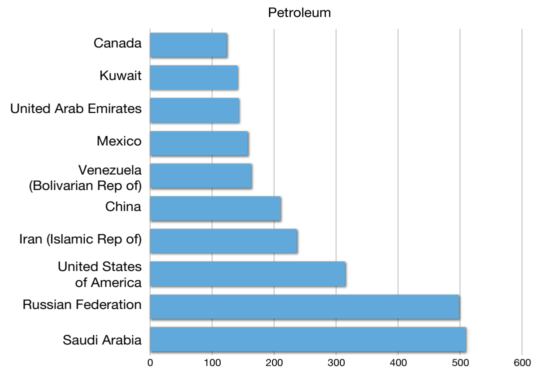
Petroleum production follows a similar pattern to that of natural gas production, with the ten largest producers accounting for 62 per cent of global production, and the top three producers (Saudi Arabia, the Russian Federation and the United States) accounting for the rest. The United States is again the sole populous nation among the top producers (see Figure 47). It is to be noted that some producer countries sell the primary petroleum product and have no significant refinery capacity.

Largest producers of fossil fuels – coal, natural gas and crude oil, million tons, 2008

Figure 47







Source: EA Energy Statistics (IEA, 2011a, 2011c). *Original* IEA categories of Crude Oil and Natural Gas Liquids have been aggregated into one 'Petroleum' category here.

The strong and consistent mismatches seen between production and population for petroleum and natural gas, compared with coal, can, to a large extent, be explained by their higher energy densities and unit values, and by the relatively high and homogeneous quality required during final consumption. This is particularly true for petroleum. High unit values render the cost of transport over long distances less of a barrier. When long-distance transport costs become a less significant component of the final cost to a consumer, international trade becomes increasingly viable. In such cases, the difference in quality between competing deposits, and the impact it has on EROEI in the extraction and processing phase, becomes a more important determinant in the exploitation of deposits. Ease of extraction and low processing requirements are more important considerations than distance from the point of view of final use. Although the global production of petroleum is much lower than for coal, we see that petroleum is far more important as a globally traded commodity. This pre-eminence is even greater in value terms than in volumetric terms. The preference for quality over quantity in favour of petroleum is also indicated by the fact that, of the four largest producers, only Saudi Arabia was listed among the top four with respect to petroleum reserves, according to OPEC (2011). In contrast to this, all top four coal producers are endowed with the highest coal reserves, according to BP (2007).

The largest exporters of coal, according to 2008 data, were Australia, Indonesia and Russia. Australia exported 20 per cent more than

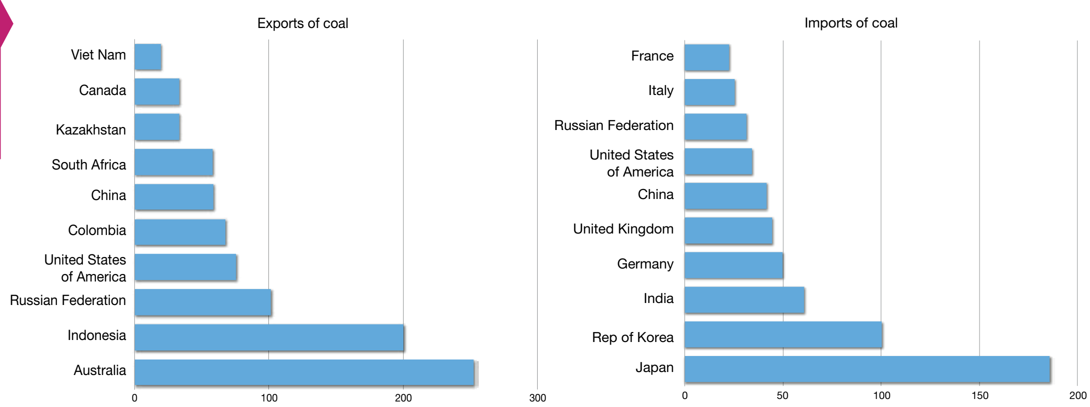
Indonesia, and more than twice the volume of Russia. While the bulk of international coal trade comprises high quality thermal coal36, nearly half of Australia's coal exports are metallurgical coal, a product for which high quality is more critical than proximity to market. In this regard metallurgical coal resembles petroleum.

In 2008, Japan led the market for coal imports, followed by Korea and India, mainly for electricity generation for power manufacturing and urban households (see Figure 48).

36 The main use of metallurgical coal is to make coke for use in blast furnace production of iron from iron ore. In comparison to thermal coal, "hard" coking coals have a key additional quality requirement, in that the coke they produce must be both strong enough, and fragment into the right particle size distribution, to allow sufficient air flow within a blast furnace. High quality hard metallurgical coal can, to some extent, be blended with lower quality coals and retain the desired characteristics, but substitutability is limited. An indication of this is that China and India, both with large domestic coal extraction industries, were respectively 97% and 89% self-reliant for thermal coal in 2010 (based on IEA figures), however their degree of self-reliance fell to 90% and 54% respectively for metallurgical coal.

Figure 48

Largest exporters and importers of coal in 2008, in million tonnes

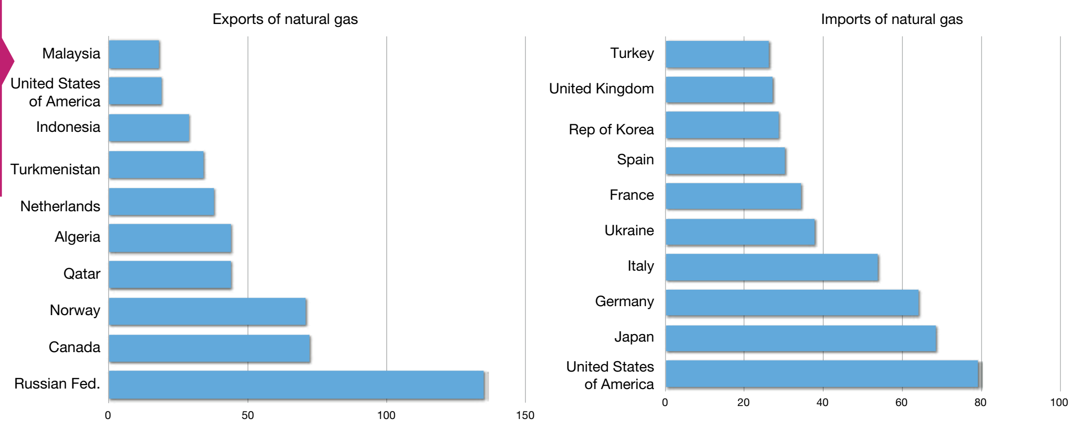


Source: *IEA* Energy Statistics (IEA, 2011a, 2011c).

Most natural gas exports in 2008 were sourced from Russia, Canada and Norway, and the main importers were high-income countries such as the United States, Japan, Germany and Italy (see Figure 50). Russia's proximity to the European market permits efficient and accessible transport via pipelines, which drives its extremely large share of exports. Norway's exports also stem from its proximity to Europe, while Canada exports to the US market for similar reasons.

Figure 49

Largest exporters and importers of natural gas in 2008, in million tonnes

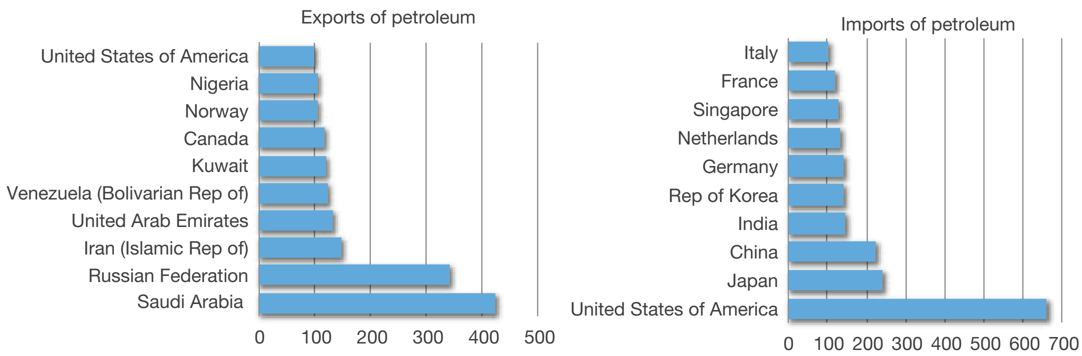


Source: *IEA* Energy Statistics (IEA, 2011a, 2011c).

The largest petroleum exporter in 2008 was Saudi Arabia. Russia was the second largest, exporting around 80 per cent of Saudi Arabia's levels, while Iran and the United Arab Emirates, in third and fourth positions, respectively, supplied at levels less than a half to a third of Saudi Arabia's exports. The United States was the largest importer of petroleum, at 600 million tonnes, which was almost three times as much as Japan and China – the second and third largest importers.

Figure 50

Largest exporters and importers of crude oil in 2008, in million tonnes



Source: IEA Energy Statistics (IEA, 2011a, 2011c).

Physical trade balances by region and country: issues of import dependency and supply security

The physical trade balance provides insights into a country's dependency on natural resources beyond its own territory. A country with a positive physical trade balance relies on other countries whereas a negative physical trade balance implies that the country is in a position to be a net exporter of resources.

In the case of fossil fuels, Africa, Asia and the Pacific, and Latin America were net exporters in terms of their physical trade balance. In 2008, Africa was the largest net exporter of fossil fuels, mainly petroleum, at 450 million tons. Asia and the Pacific has reduced its net exports to around 300 million tons in the past two decades, compared to over 750 million tons in the 1970s.[37] Until the 1990s, the region was also a small net importer of coal. Latin America has become an important net exporter of fossil fuels, especially petroleum, with 250 million tons in recent years. A high quality of thermal coal sourced from Colombia is also increasing the region's net exports of coal.

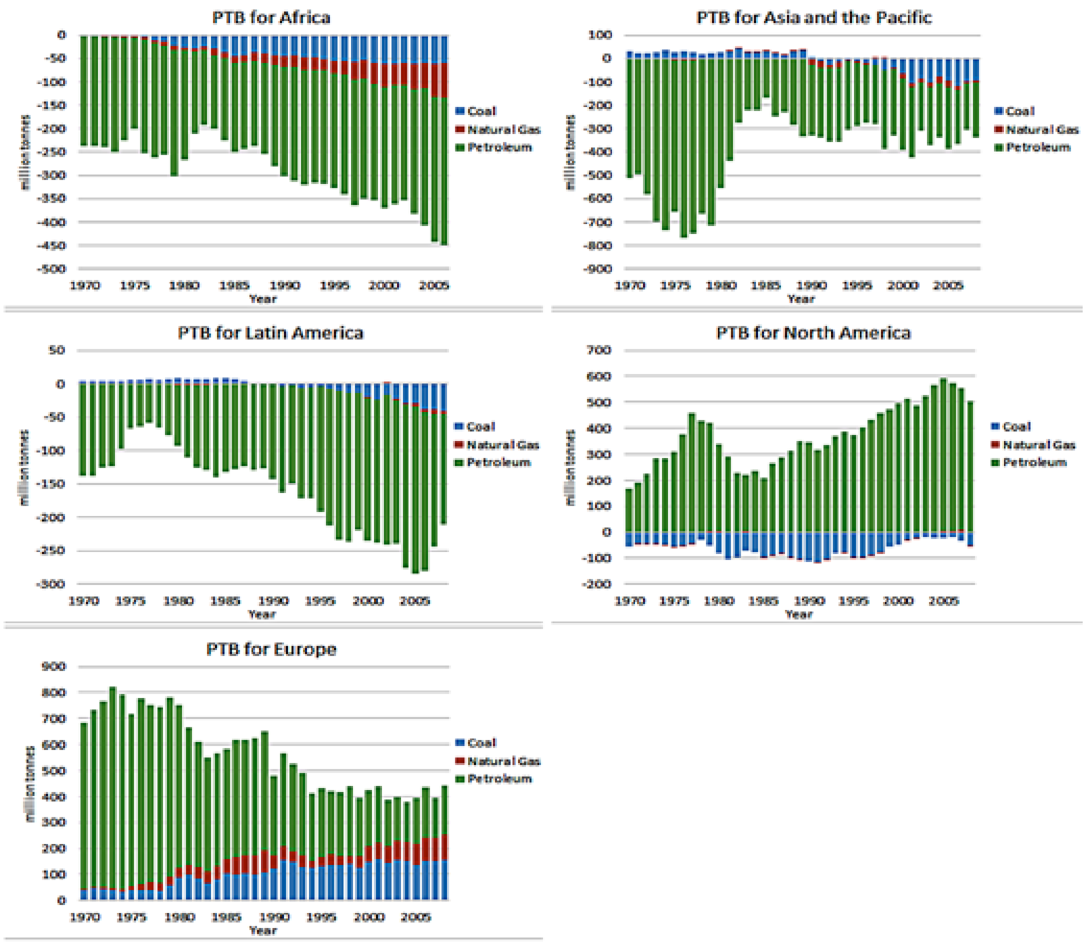
North America and Europe, on the other hand, have been net importers of fossil fuels for the past 40 years. In North America, petroleum imports grew strongly until 1977, at which point they declined rapidly for around a decade, particularly during the second oil shock crisis in 1979. The prolonged period of low petroleum prices from the mid-1980s until 2004 sparked a strong growth in net imports, peaking at just under 600 million tons in 2005, but net petroleum imports then declined to 500 million tons by 2008. This latest decline has been the combined result of resurging oil prices since 2004 and mitigation of demand. Resurgent oil prices made domestic production economically viable, in particular production from 'non-conventional' sources, such as oil sands reservoirs, though the reservoirs required intensive hydraulic fracturing for recovery. North America was a net exporter

37 Note that 'Asia and the Pacific' as defined in this report includes most of the oil-rich states of the Middle East, which come under 'Western Asia'. Results at the sub-regional level can be radically different, with the highly populous, Eastern Asia and Southern Asia regions being strongly dependent on net imports of fossil fuels.

of coal and natural gas, most significantly of coal in the 1980s and 1990s. In contrast, Europe has been a net importer of all types of fossil fuels, but managed to reduce its import dependency in the 1990s to a stable 400 million tons per year. By 2008, Europe was importing roughly equal shares of petroleum and coal, with a rapid rise in the share of natural gas, largely at the expense of petroleum (see Figure 51).

Figure 51

Physical trade balances for fossil fuels for 5 world regions, 1970–2008,



Source: CSIRO Global Material Flow Database

Upstream requirements of fossil fuel trade

International trade in fossil fuels is a huge enterprise, and hence requires large material and energy inputs for the construction of the associated infrastructure (ports, ships, pipelines, etc.), and for ongoing operations. Wiedmann *et al.* (2013) quantified those upstream requirements as Raw Material Equivalents (RME), using a global multi-region input-output model and arriving at an estimate of approximately 7.5 billion tons. This is nearly 60 per cent of the 12.8 billion tons of RME associated with all consumption of fossil fuels, giving some indication of the importance of the international trade in the fossil fuels sector. It constitutes about 11 per cent of the total 69.7 billion tons of global resource extraction associated with all economic activity in 2008.

While the upstream requirement appears substantial, it should not be perceived as impost or excessive material requirement that could be avoided if there were trade in fossil fuels. In fact, the total upstream inputs generated by fossil fuels trade is potentially less than the requirements in an alternative scenario of locally sourced energy. Most of the RME associated with traded fossil fuels would inevitably be associated with that fuel anyway. A detailed, quantitative treatment of that topic is beyond the scope of this study, but some aspects are discussed below.

In a scenario of locally sourced energy, the most significant reduction would occur in relation to the direct energy requirement for the international transport and export of fossil fuels. The detailed breakdown of energy use by sectors given in IEA (2011d) allows one to estimate an upper limit for this. The ratio of energy used in international marine bunkers plus the energy used in pipeline transport, to the total energy content of energy exports, was estimated for a sample of 17 countries. All 17 countries exported more than 50 per cent of their total energy production (IEA, 2011d, 2011e).The median value for transport energy used was 0.64 per cent, with only two countries above 2 per cent. This can be taken as an upper limit for the transport energy requirements of international fossil fuels trade, as the estimate includes energy used for all international ship-borne trade (not just fossil fuels) and the energy required for all pipeline transport operations (where reported). It implies that the energy used directly in the international transport of fossil fuels trade is less than 2 per cent of the total energy contained in the traded commodities.

The concept of energy return on energy investment (EROEI) enables this impact to be compared to a scenario of locally sourced energy. It needs to be appreciated that the lower the EROEI of a fuel source, the higher its upstream material and energy requirements per unit (see footnote 38, below). Maintaining the value for transport energy at 2 per cent, we find significant and rapid declines in EROEIs of most of the different energy sources studied by Murphy and Hall (2010). The most significant fall estimated was for coal, from 80 at the mine-mouth to 31 after it was shipped abroad. If oil were produced at the world average EROEI for 1999, this would decrease from 35 to 21. The decline would be less significant, from 10 to 8.3, for natural gas, if it were produced at the EROEI calculated for the U.S. in 2005. It would not be significant at all in the case of oil derived from tar sands (from 3 to 2.8).[38] These estimated calculations illustrate the point that it is the specific characteristics of source deposits and extraction/beneficiation processes that determine a net increase or decrease in the upstream requirements of fossil fuels trade. Indeed, the rapid deterioration in EROEI for oil imported into the US between 2005 and 2007 (from 18 to 12), indicated in Murphy and Hall (2010), can largely be explained by the increased share sourced from Canadian tar sands, implying an increase in upstream requirements. Instead, if high EROEI, conventional oil were to be imported, and substituted for low EROEI oil from marginal domestic fields, total upstream requirements could be expected to decrease.

It is almost certain that the strong demand for fossil fuels will continue, and that large amounts of fossil fuels will be traded despite a further concentration of supplier countries and demand centres. Future demand will be driven by the rising middle-class consumers created by the continuing industrialization and urbanization of developing countries. Fuel subsidies will continue to artificially reduce the price of fossil fuels, further ratcheting up demand. A move to decentralized renewable energy supply would result in reduced demand for and trade in fossil fuels, and create a new segment in international trade around renewable energy technologies and installations. A shift in subsidies and tax exemptions from fossil fuels to renewable energy would support such a transition and would have equally large environmental benefits in the form of reduced greenhouse gases.

38 Using the definition EROEI = Gross Energy Yield / Energy Expended, an EROEI of 80 on coal at the mine-mouth means that only 1.25% (i.e. 1/80) of the energy equivalent contained in the coal was consumed in getting it to that stage. If we then use another 2.0% of the contained energy in transporting it internationally, the EROEI drops to 100% / (1.25% + 2%) = 30.77. In contrast, for the tar sand example, an EROEI of 3 means that 33.3% of the contained energy is used in just extracting the oil. Transporting the oil will cause little change as post-transportation EROEI = 100%/(33.3% + 2%) = 2.83. Note that the range of EROEI given here are not meant to be indicative of current EROEI for different energy sources. Rather, they were chosen to illustrate the different relative effect the impost of international transportation would have on different fuels, which start out with different upstream EROEI levels prior to export.

Credit: DFID - UK Department for International Development, flickr

5. Conclusions

This report assesses international trade with a particular focus on the biophysical flows of natural resources. Global annual extraction and use of natural resources – non-renewable resources such as minerals and metals or fossil fuels as well as renewable resources such as biomass or fresh water – have increased about eight-fold during the past century, and are still increasing rapidly. International trade is growing even faster, and plays an important role in responding to rising demand: it facilitates access to resources that are no longer sufficiently available within the countries themselves.

The report focuses on resource use and the upstream resource requirements of trade, and thereby adds novel information to the discussions on resource use and resource efficiency, decoupling and dematerialization. It represents a first attempt to show in a comprehensive way the scientific literature on trade-related biophysical flows, a literature that has greatly increased in recent years. The resources covered are materials (including fossil energy carriers), water and land, across a time period from 1980 (or earlier, where possible) to 2010.

On the basis of the existing literature, it seeks to provide answers to the following questions:

1. How important is trade for supplying countries with resources? How is trade dependency distributed, and how does it change over time?
2. What roles do countries occupy in international trade, where are the centres of use and demand, and where are the locations of international supply of resources? What factors determine this distribution?
3. What are the upstream resource requirements, in terms of materials, water and land, of traded commodities? How large are they, how are they composed and how do they change over time?
4. Finally, what can be concluded from the answers to the above questions about the contribution of trade to the efficiency of global resource use?

QUESTION 1

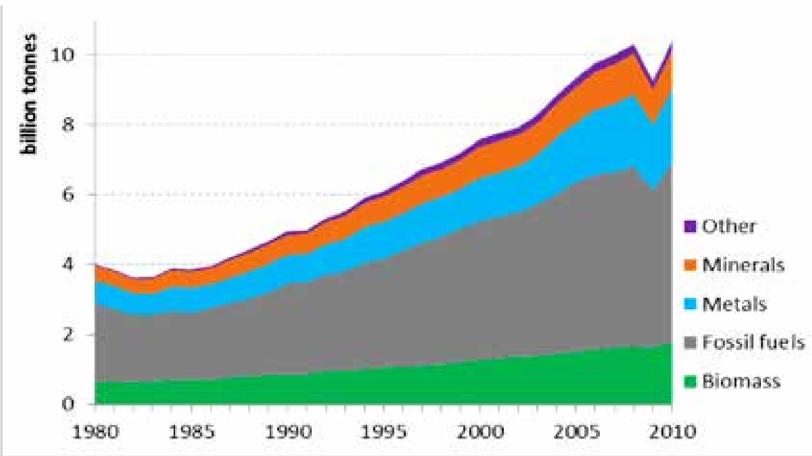
How important is trade for supplying countries with resources, and how does dependency on trade change over time?

Of all material resources extracted and used worldwide (65 billion tons in 2010), about 15% (about 10 billion tons) are traded. During the three decades from 1980, traded volumes increased by a factor of 2.5 (see Figure 52), while the amount of resources extracted and used globally also increased, but to a lesser degree (by a factor of 1.8). Thus, the overall importance of trade for supplying countries with the resources they need has increased.

Physically, natural resources or commodities at a very low level of processing dominate international trade: manufactured products only amount to 20% of trade volumes (while in monetary terms they amount to 70%). The lion's share of trade is taken up by fossil fuels: they make up half of all traded mass, while mining products (metals and minerals) follow next with about 20%, the remaining share of little more than 10% being biomass (see Figure 52). Half of the volume of fossil fuels extracted is reallocated through trade; about the same applies to metals (if considered in terms of metal content and thus the economically valuable part of gross ores). Thus the unevenly distributed resources that are, at the same time, key ingredients of industrial production are highly dependent upon international trade. However, the largest component of domestic extraction, namely minerals for construction (limestone and sand), is hardly traded at all. Biomass, such as food, being an almost equally ubiquitous material, is also mainly supplied domestically. Nevertheless, if domestic supply does not suffice to feed the population (which is the case in several countries in the Near East, but recently in China, too), trade becomes highly critical.

Figure 52

Physical trade according to material composition, 1980–2010



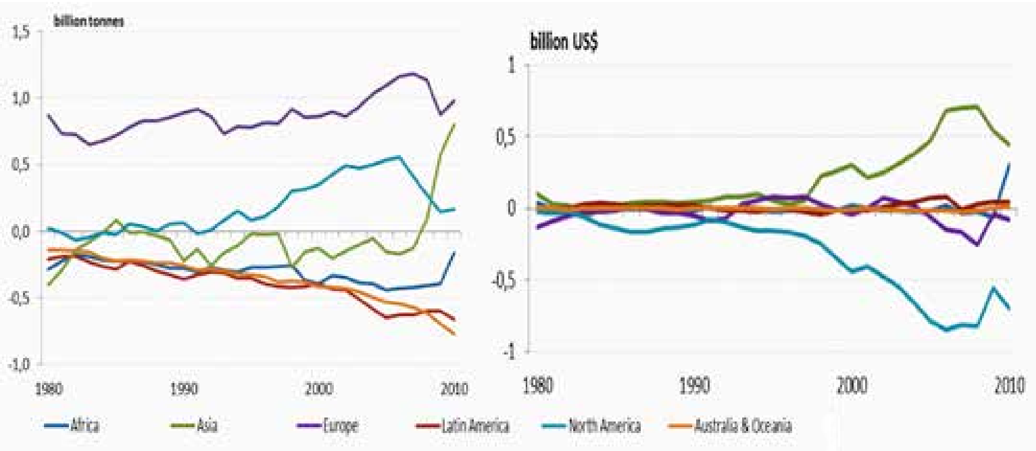
Source: Dittrich, 2012; physical trade measured as (imports + exports)/2. Manufactured products (about 20% of total trade) are assigned to the resource categories they consist of proportionally. The group of 'other' materials could not be assigned – it consists largely of (mineral) water and other beverages.

Another way of looking at trade dependency is through trade balances. In economic terms, a country's trade balance is positive when the value of its exports is higher than the value of its imports. In physical terms, on the other hand, a country's trade balance is positive when the weight of its imports is higher than the weight of exports. In general, and for clear economic reasons (for example, changes in exchange rates), trade in economic terms is fairly balanced. In past decades, North America was the only world region with a consistently negative monetary trade balance, while Asia had a consistently positive trade balance – all other world regions balanced around zero (see Figures 53 and 54).

With regard to physical trade volumes, deviations from zero are much more common. Physically, Europe had a consistently positive trade balance (i.e. imported higher volumes than it exported) and, lately, also North America and Asia. Negative physical trade balances were the pattern in Africa, Latin America and Australia/Oceania.

Trade balances by continent in physical (left) and monetary (right) terms, 1980–2010

Figure 53

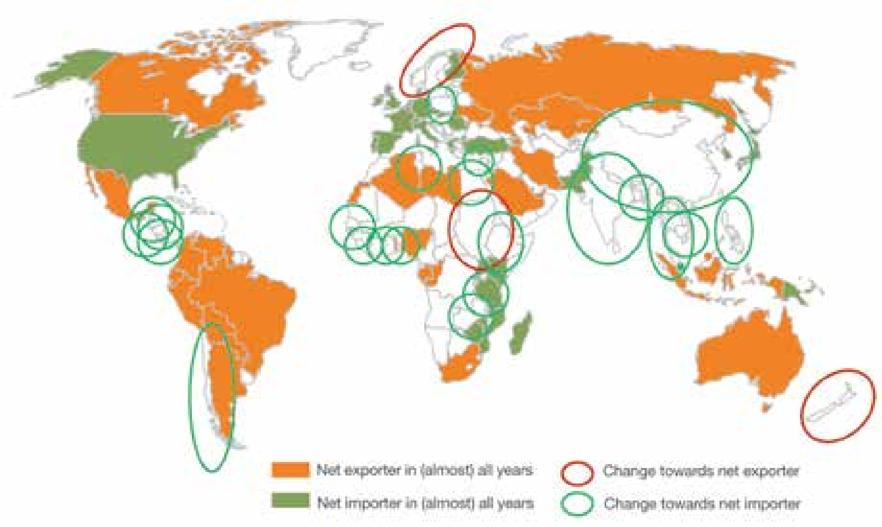


Sources: Physical terms: Dittrich, 2012, monetary terms: UNComtrade, 2012; n.b. while monetary trade balances are counted as exports minus imports, physical trade balances are counted as imports minus exports

China stands out: physically, it is the world's largest importer, followed by EU27, Japan, South Korea and the United States, but economically, its trade balance is also highly positive. At the other extreme, Australia is the largest (physical) net exporter (followed by the Russian Federation and Brazil), with a broadly neutral monetary balance of trade.

Persistence and change in net-importing and net-exporting countries, 1962–2010

Figure 54



Source: Dittrich *et al.*, 2012

Questions

In 2010, 30% of all countries were net suppliers of materials to the world markets, while 70% of all countries were net importers of them. South American countries, Canada, Scandinavia, West and Central Asian countries, as well as Australia and the South-Eastern Asian islands, had been and remained the largest suppliers of materials. With regard to net imports, the United States, Japan and the West European countries remained large importing countries throughout recent decades. During the time period observed, many countries shifted towards becoming net-importers of resources (see Fig. 54) and only very few countries turned to becoming net exporters (only the Sudan, New Zealand and Norway). While the number of net exporters is decreasing, they are increasing their export volumes in order to meet the growing demand on the world market.

Dependence on material imports has increased in most economies during the past three decades, as most countries have increased their imports faster than their domestic resource extraction. Import dependency has increased with regard to all material categories, but is of course highest for fossil fuels and metals. In 2008, more than 100 countries (1980: 85 countries) imported more than half of their fossil fuel requirements and 97 countries (1980: 75 countries) imported more than half of their metal requirements. Dependence on biomass imports has increased for countries with unfavourable bio-geographical conditions. This is the case in 17 countries (1980: 9 countries), mainly small islands and West Asian countries such as the Seychelles or Kuwait, which imported more than half of their biomass requirements.
In fact, dependence on the world market for delivering vital commodities is increasing sharply around the world. Global interdependency is rising, and with it the vulnerability of this global trading system: its balance relies on ever fewer resource producers.

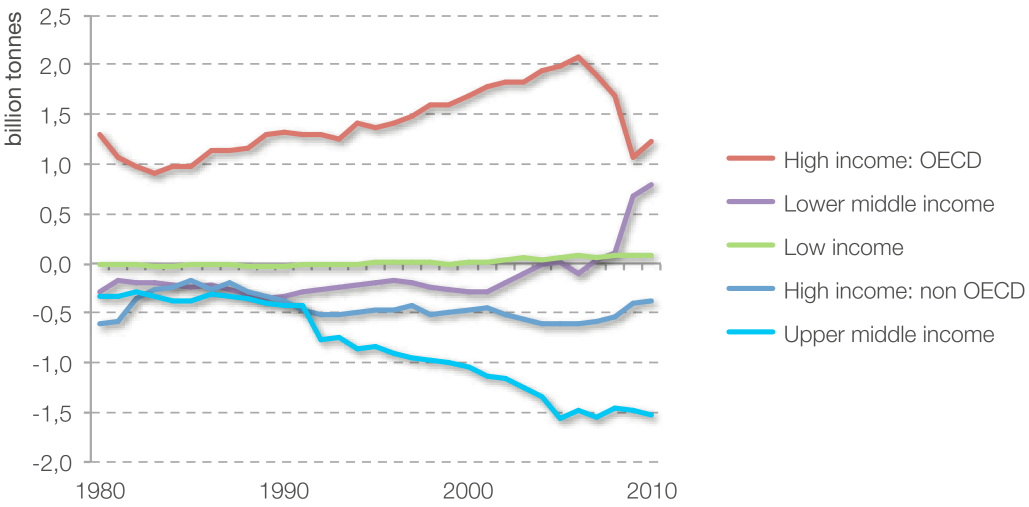
QUESTION 2

Which roles do countries occupy in international trade, where are the centres of use and demand, and where are the locations of international supply of resources? What factors determine this distribution?

Throughout the twentieth century, global trade patterns followed income patterns. High-income industrial countries imported a large amount of resources from countries which, in the main, had low income levels, and exported a smaller (but more valuable) amount of processed goods among themselves. Up to the 1980s, only high-income OECD countries were net importers of materials, while all other countries were net suppliers. However, this pattern is changing somewhat. In recent decades, non-OECD countries with high incomes (mainly oil-exporting countries), countries with an upper-middle income, such as Russia, Brazil and South Africa, and some high-income OECD countries, such as Australia, Canada and New Zealand, increased their supplies to the world market and became important suppliers of materials. At the same time, countries with lower-middle incomes changed from being suppliers to being importers and increased their net imports dramatically. The most spectacular case of this type is China (see Fig. 55 and 56).

Figure 55

Countries' physical trade balances (PTB) by income group, 1980–2010

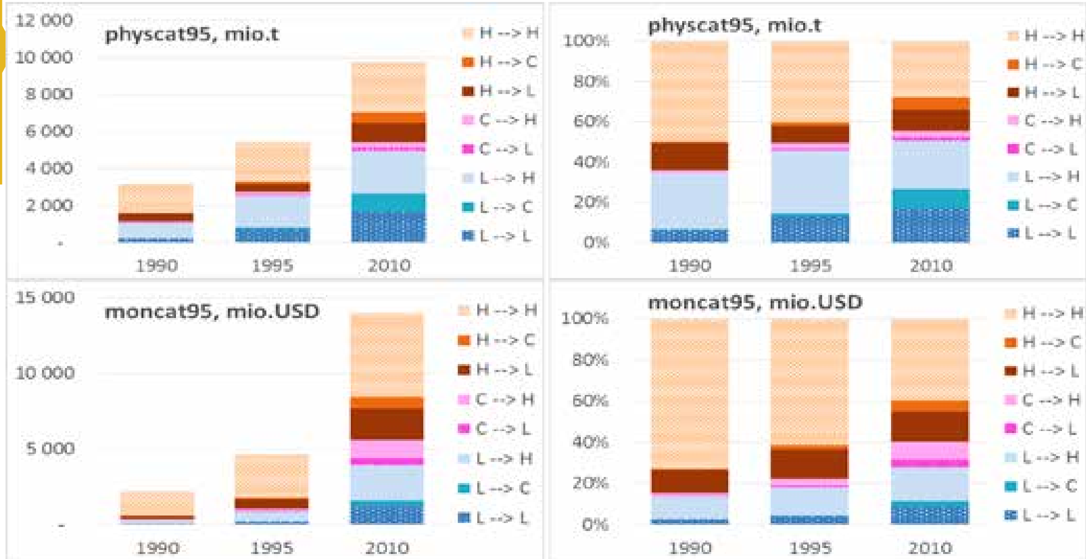


Source: Dittrich, 2012; Assignation according to World Bank, 2011.

While income is gradually losing some of its influence upon the supply of resources, another variable is gaining in influence: population density. Increasingly, sparsely populated countries are supplying materials, more or less irrespective of their income. The material volumes reallocated from sparsely to densely populated countries tripled between 1980 and 2008. Population density can be looked upon as a proxy for low per capita resource endowment, as is confirmed by the World Bank indicator for respective resource endowment. Only the 10% most resource-rich countries (15 countries in absolute numbers) have been net suppliers of materials to world markets in the past decade (Dittrich *et al.* 2012). Nevertheless, there are also some exceptions. Some of the most resource-rich countries, like the USA, were net importers, and some relatively resource-poor countries, like Guyana or Latvia, were net exporters of materials. On the other hand, densely populated but resource-rich countries, like China and India, have become major importers.

Figure 56

Global world trade by countries' income group 1990-2010



source: PIK bilateral trade data base, Comtrade, Pichler *et al.* forthcoming. Countries are classified by their income in 1995, according to World Bank. L= low, lower-middle- and upper-middle-income countries according to WB, H= high-income countries.

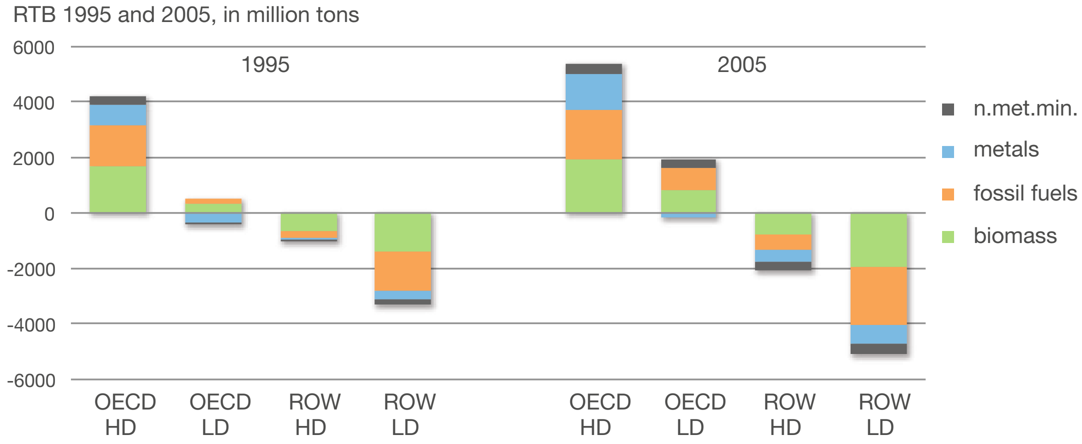
As a very recent study has shown (Pichler *et al.*, forthcoming), the overwhelming dominance of high-income industrial countries in world trade has given way to more trade between developing countries. In part, this is due to China acquiring a strong role in world trade; but even if China's activities are separated from the rest of the lower-income countries, the role of the lower-income countries has become much stronger nonetheless (see Ch.2). Between 1990 and 2010, the share of developing countries' intraregional trade in total physical trade (as well as in monetary trade) increased substantially (see Fig. 56). Half of this effect is due to China, which contributed 11 percentage points to the increase in the share of physical trade and 6 percentage points to the increase in the share of monetary trade. Although intraregional trade between high-income countries has still the largest regional trade volume, its relative share in total trade has significantly declined, from 50% in 1990, to 40% in 1995, and to 28% in 2010.

These recent structural changes coincide with changes in the trend of resource prices. During the twentieth century, rapidly growing resource use coincided with decreasing prices. Developing countries were predominantly providers of raw materials. These basic products from the South were produced with the use of relatively cheap natural resources and unqualified labour, whereas the imported products from the North were capital- and knowledge-intensive and relatively expensive. Over the period 2000 to2012, resource prices rose. As a result, extraction and export of resources became more attractive, resource-rich countries gained political and economic power, and high-income countries became major resource providers, too. While prices have recently fallen back, further growth in demand in emerging economies and continuing population growth are likely to generate further upward pressure on prices in the future.

What remains unchanged is the role of high-income countries as the main recipients of resources via trade. Europe has the most pronounced positive physical trade balance of all continents (see Fig. 53), and OECD countries in general consistently score high on physical trade balances (Fig. 55 and Fig. 56). Population density matters: high-density countries, particularly, depend on receiving resources through international trade, but in recent years, several low-density OECD countries, also, have shown positive physical trade balances. Non-OECD low-density countries increasingly supply resources to the world market (Fig. 54).

Figure 57

Raw material trade balances (RTB) between OECD countries and the rest of the world 1995 and 2005, by population density (HD is high, and LD is low, population density)



Source: Bruckner *et al.* (2012)

As the consumption-based indicators of global trade show, this shift mainly takes place among the suppliers of resources. At the receiving end, expressed in terms of material footprints, which show both the direct and the indirect consumption of the world's resources, the high-income countries/regions such as the US, Europe and Japan still stand out (see Chapter 3).

Since the turn of the century, therefore, the long-term patterns of 'unequal exchange' seem to be undergoing a certain change. Major changes already occurred during the 1980s, when several emerging economies started to liberalize their trade and to enter the world market. This trend has become even stronger since the turn of the century, and the relations between the high-income industrial countries and the developing countries have become rather more symmetrical.

QUESTION 3

What are the upstream resource requirements of international trade?

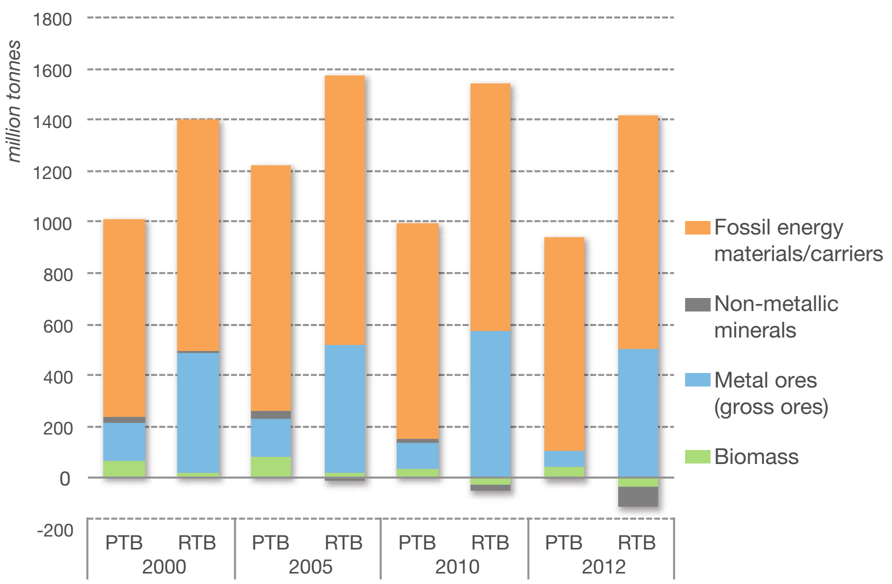
Foreign trade statistics consider trade flows on the basis of the current mass or energy content or the monetary value the goods have at the time they cross state borders. The resources used in the country of origin for producing the traded product are "upstream material requirements". Trade accounts that include upstream requirements communicate the total resource requirements of final consumption.

Approaches accounting for upstream material requirements have been the subject of intensive research efforts in the past decade. The estimation of material resources embodied in trade is done via two approaches. The first approach uses environmentally extended multi-regional Input-Output Models (MRIO) to trace inter-industry deliveries through the economy and between economies down to final demand categories. The second approach uses coefficients from Life Cycle Assessments (LCA) of products, which are multiplied by the value of traded goods in order to calculate the upstream material, energy, water or land requirements. These two approaches can be combined into so-called "hybrid" approaches. All approaches share a common feature: they employ a consumption perspective whereby all resource use along the life chain of products is attributed to the final consumer (and the country of final consumption). The findings from these studies are not yet very conclusive; the studies rely upon different methods or combinations of methods, and therefore produce different results.

While physical trade balances (PTB) relate the amounts of goods imported to those exported by their weight at borders, raw material trade balances (RTB) add upstream resource consumption to the weight of the goods at borders. The consumption levels associated with high income and high imports have, as might be expected, a stronger impact on RTB than on PTB.

Figure 58

EU27 physical trade balance (PTB) and raw material trade balance (RTB)



Source: Eurostat, 2014

For EU 27, for example, the European Statistical Office (Eurostat) has documented raw material trade balances (RTB) as being about 40% higher than physical balances of direct trade (PTB). Since about 2005, both trade balances have slightly declined (Fig. 58). In all cases, metals and fossil fuels dominate the picture.

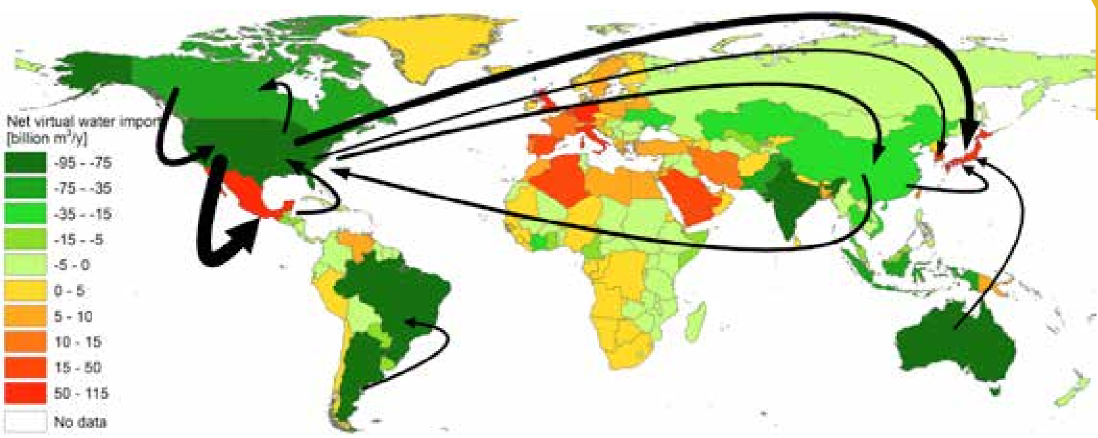
According to findings based on MRIOs, high-income countries have in the order of 50-100% larger positive trade balances, when measured in raw materials rather than by direct trade, while for low-income countries the opposite is true. Findings based on LCA methods show that upstream materials embodied in trade amount to four times the weight of directly traded products and have been rising over-proportionally during recent decades (Chapter 3).

A specific research tradition deals with upstream requirements of water, called "virtual water" (usually estimated for crops, but more recently for industrial products also). Trade flows between countries can be represented in terms of virtual water flows, and country-level balances can be calculated (see Fig. 59). Most countries in Europe, the Middle East and North Africa are net importers of virtual water. Japan, South Korea, and Mexico are also notable importers. The largest virtual water exporters are found in North and South America, as well as South and South-East Asia, and Australia.

Virtual water studies can also determine how much water a country saves by importing goods that have needed water for their production somewhere else, compared to their estimated water requirement if they had been produced domestically. These results can further be analysed as global water efficiency: producing food in regions of low precipitation and high evapotranspiration, for example, requires much more water than in regions with different climatic profiles. Thus, it is possible to calculate global water savings due to trade; the amounts saved by trade are estimated to be in the order of magnitude of between 500 and 1600 km3 annually and are rising (Chapters 3 and 4.1).

Figure 59

Virtual water balance per country and direction of gross virtual water flows related to trade in agricultural and industrial products over the period 1996–2005



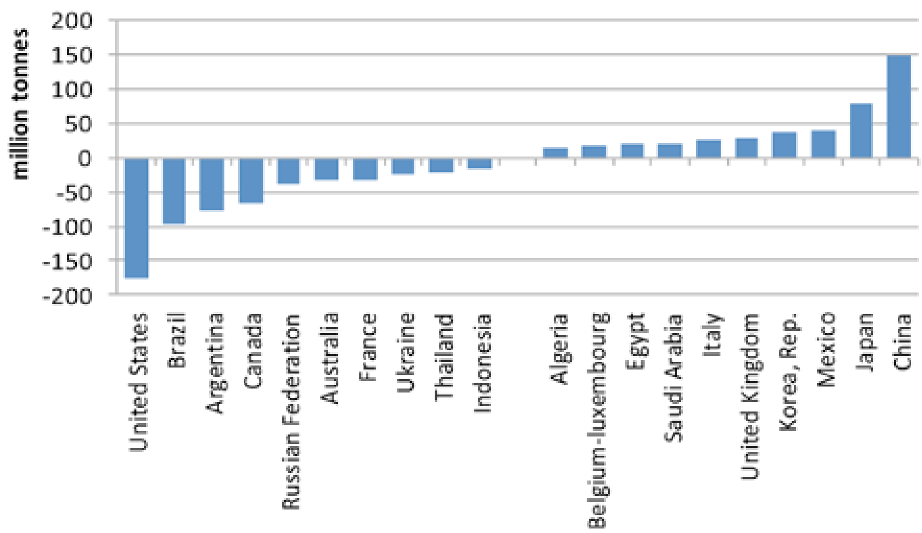
Source: Mekonnen and Hoekstra, 2011. Only the biggest gross flows (>15 Gm3/y) are shown.

Another research strand deals with land embodied in biomass trade (Chapter 4.1). Biomass-exporting countries are typically countries with low population density and high amounts of available land per person. About 16% of the global cropland area is linked to international trade. North America, Oceania and South America have between 5ha and 8ha per person available, while the European Union, South East, Eastern and Southern Asia have at their disposal only 1ha/person or less. The latter regions are close to the maximum productivity of their available land, and they have the highest imports of biomass produced on land elsewhere. More subtle accounts refer to HANPP (that is, primary productivity) as embodied in trade;

HANPP not only captures the amount of land, or the amount of agricultural land required for a traded product, but also its productivity. International trade is already indispensable for supplying the necessary nutrition in a number of world regions, in particular Middle Eastern and North African countries.

Figure 60

Trading biomass (products): top 10 net-importing and net-exporting countries

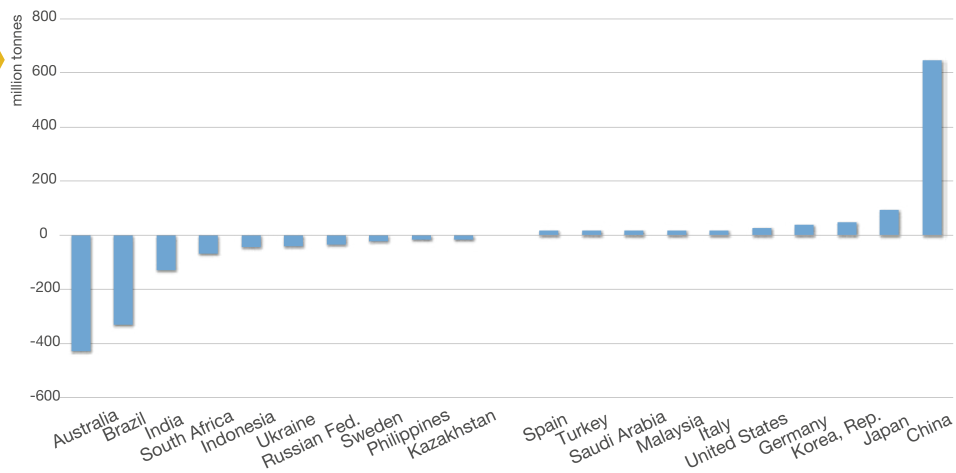


Source: Dittrich (2012)

In contrast to biomass, metals are non-renewable materials and each extraction reduces the respective deposit. Also, a majority of them are extracted for export. Environmental problems linked to metal extraction are manifold, and as the ore grades of most mines worldwide are declining, these problems tend to increase: upstream requirements of metal trade are rising faster than direct trade. The environmental burden of metal extraction is mainly borne by countries with a low population density, in the North and the South. , ever larger amounts of metals are being extracted (rising from 3.6 billion tons in 1980 to 6.7 billion tons in 2008), and 2.3 billion tons are traded, mostly as metal ores and concentrates; Asia (in particular China) and Europe are the regions that import most. Australia and Brazil are the main suppliers (Fig. 61).

Figure 61

Top 10 net suppliers and net importers of metals in the year 2010

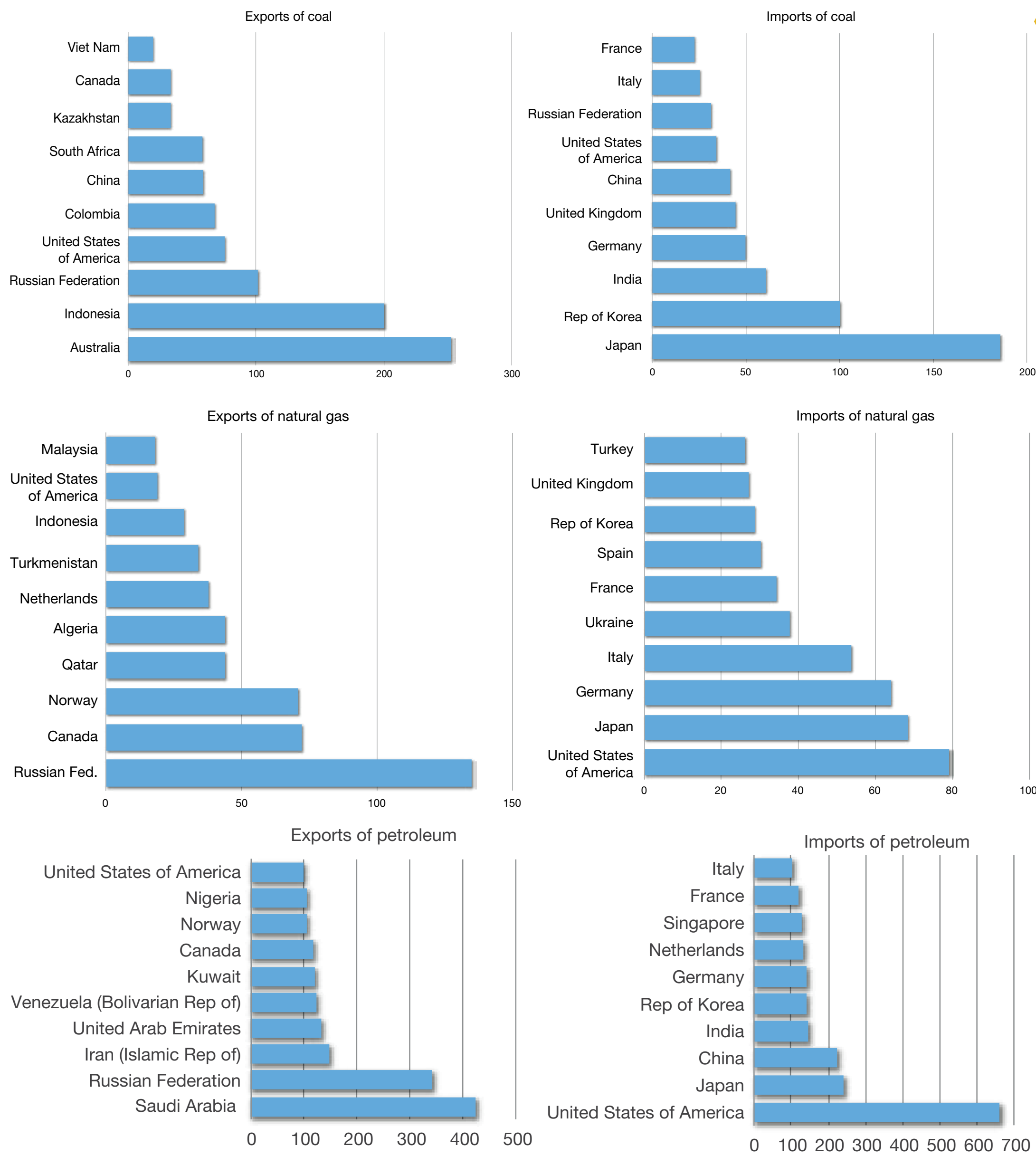


Source: Dittrich, 2012

Possibly, the strongest geographical mismatch between supply and demand pertains to fossil fuels. Their extraction and use has grown by an annual rate of 1.9% since 1970, with coal being extracted both in the highest amounts and with the highest growth rates. Coal is geographically not as concentrated as natural gas and petroleum. By far the largest producer is China, but the largest exporters are Australia and Indonesia. The largest importer of coal is Japan, followed by Korea and India. With regard to natural gas, Russia leads as an exporter, while the main importers are the USA, Japan and Germany. Crude oil is exported mainly by Saudi Arabia and Russia; the USA is the largest importer. The physical trade balances of fossil fuels, ever since 1970, have been strongly positive for Europe and the USA, while all other major world regions have had negative balances (see Chapter 4.3).

Figure 62

Top ten exporters and importers of coal, natural gas and petroleum in 2008 (million tons)



Source: IEA Energy Statistics (IEA 2011a, IEA2011b).

Questions

Given the current data situation, it is very difficult to estimate the quantitative relation between the amounts of resources traded (direct trade) and the burden of upstream requirements they carry with them. Depending on resource and estimation method, upstream resource requirements range between 40% and 400% of the traded materials. As far as material requirements are concerned, the quantities exchanged by international trade are growing faster than global material extraction.

An approach recently developed is the calculation of countries' "material footprints". Material footprints express the amount of resources a country requires to satisfy the consumption of its inhabitants, regardless of whether the respective resource flows occur domestically or in the countries of origin of the commodities consumed. Material footprints are calculated with the help of environmentally extended multi-regional input-output models, which allow calculation of the distribution of all globally extracted resources according to the end use in each country.

Depending on the model used (such as EORA with Wiedmann *et al.*, 2013, or EXIOPOL with Tukker *et al.*, 2014), results differ slightly. What they do have in common, however, is the finding that the difference between high-income (and high-consumption) countries and lower-income countries is much more pronounced than with direct trade flows and the associated raw material equivalents. The material footprint analysis brings income differences to fully bear on differences in resource use: accounting for the consumption of textiles imported from China to the UK, for example, not only includes all resources directly used in the production chain of these textiles, but also takes account of Chinese investments in the infrastructure required for producing and exporting them. This infrastructure, one might argue, not only serves the UK's consumers now, but also allows the exporting country, in this case China, to build its future.

QUESTION 4

Does international trade improve or worsen the global efficiency of resource use?

Trade theory would suggest that trade contributes to the environmental efficiency of resource use by allowing the extraction of resources and the production of commodities in places where the least wastage occurs (or, in other words, the smallest amounts of wastes and emissions are produced, assuming that these are accounted for in the relevant markets). The increase in international trade, therefore, should gradually improve the quantitative relation between traded products and the upstream resource requirements for producing them. However, other mechanisms may cause upstream requirements to increase faster than the volume of traded products. There are many potential mechanisms of this kind (see below), though they cannot be distinguished by this report's overview of existing efforts to describe the amount and dynamics of upstream resource requirements.

The evidence in this report suggests that upstream resource requirements of trade are, for the most part, rising, whether they are accounted for in materials or water, and by whatever method. Various factors may be driving this growth: firstly, an increasing share of higher-processed goods in total trade; secondly, higher trade activities in general (i.e. more intermediate goods are traded between countries, with additional transport, before they end up satisfying final demand). At the same time, declining ore grades for metals and industrial minerals as well as declining energy returns on energy investment (EROEI) for fossil fuels can be observed (see Chapter 4.3). Such changes raise the upstream requirements for these commodities, since they need a higher material and energy input per ton of tradable good. The increasing consumption of fossil energy carriers for fuelling transport is another factor driving growth in upstream requirements. Finally, population growth and increasing food demand in arid regions draw on increasing imports of crops and corresponding increases in "virtual water" embodied in trade. These factors may completely cancel out a potentially better allocation of extraction and production processes through world trade.

In the final analysis, then, the answer to Question 4 is currently undetermined. In time, the multiple current research efforts to improve methods and indicators dealing with the physical properties of international trade may yield more conclusive answers.

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About the UNEP Division of Technology, Industry and Economics

Set up in 1975, three years after UNEP was created, the Division of Technology, Industry and Economics (DTIE) provides solutions to policy-makers and helps change the business environment by offering platforms for dialogue and co-operation, innovative policy options, pilot projects and creative market mechanisms.

DTIE plays a leading role in three of the seven UNEP strategic priorities: climate change, chemicals and waste, resource efficiency.

DTIE is also actively contributing to the Green Economy Initiative launched by UNEP in 2008. This aims to shift national and world economies on to a new path, in which jobs and output growth are driven by increased investment in green sectors, and by a switch of consumers' preferences towards environmentally friendly goods and services.

Moreover, DTIE is responsible for fulfilling UNEP's mandate as an implementing agency for the Montreal Protocol Multilateral Fund and plays an executing role for a number of UNEP projects financed by the Global Environment Facility.

The Office of the Director, located in Paris, coordinates activities through

- **The International Environmental Technology Centre** - IETC (Osaka), which promotes the collection and dissemination of knowledge on Environmentally Sound Technologies with a focus on waste management. The broad objective is to enhance the understanding of converting waste into a resource and thus reduce impacts on human health and the environment (land, water and air).
- **Sustainable Lifestyles, Cities and Industry** (Paris), which delivers support to the shift to sustainable consumption and production patterns as a core contribution to sustainable development.
- **Chemicals** (Geneva), which catalyses global actions to bring about the sound management of chemicals and the improvement of chemical safety worldwide.
- **Energy** (Paris and Nairobi), which fosters energy and transport policies for sustainable development and encourages investment in renewable energy and energy efficiency.
- **OzonAction** (Paris), which supports the phase-out of ozone depleting substances in developing countries and countries with economies in transition to ensure implementation of the Montreal Protocol.
- **Economics and Trade** (Geneva), which helps countries to integrate environmental considerations into economic and trade policies, and works with the finance sector to incorporate sustainable development policies. This branch is also charged with producing green economy reports.

DTIE works with many partners (other UN agencies and programmes, international organizations, governments, non-governmental organizations, business, industry, the media and the public) to raise awareness, improve the transfer of knowledge and information, foster technological cooperation and implement international conventions and agreements.

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The availability and accessibility of natural resources is essential for human well-being. Natural resources are unevenly distributed, and the limits to their availability in many parts of the world are becoming increasingly visible. International trade has played an important role in delivering resources from centres of supply to centres of demand.

In the past few decades global efforts have been channelled to enforce sustainable management strategies for natural resources, increase resource and environmental efficiency and thus, overall human well-being. In such a context, what role does international trade play in increasing resource efficiency, reducing environmental impact and promoting equitable and inclusive growth?

Through a comprehensive review of updated data and existing literature, the latest assessment from the International Resource Panel ***International Trade in Resources: A Biophysical Assessment*** examines the rapid growth and pattern changes of resource trade and analyzes the upstream resource requirements of traded commodities including materials, land, energy and water. The report seeks to shed light on:

- the dramatic rise in international trade in recent decades, with over a six-fold increase in value and more than doubling of its volume between 1980 and 2010;
- the indirect resources associated with trade, i.e. resources used in the production process but not physically included in the traded goods;
- the increasing dependency on world markets to supply the demand for resources, across all material categories with fossil fuels and metals accounting for the highest share;
- the changes that patterns of trade dependence has experienced with high-income countries remaining main recipients of resources via trade and emerging economies, such as China, becoming major importers; and
- the rapid increase in upstream requirements of traded commodities -in terms of materials, water, land and energy - the estimates of which range widely from 40 up to 400 per cent of traded materials.

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