5. Environmental footprints

Richard Wood

5.1 INTRODUCTION

As population grows and as our societies converge towards better socio-economic outcomes, we see increasing focus on the environment, and the incorporation of interactions between the environment and our economy in planning future policy options. Since the 1970s with the Club of Rome report *The Limits to Growth* (Meadows, Club of Rome, and Potomac Associates, 1972) and further to the Brundtland Commission (World Commission on Environment and Development 1987), we see an increasing focus on environmental impacts on the global stage. The case of addressing human-induced climate change is perhaps one of the most pressing issues, in which we see the need to consider both the emission of our economy on the environment, but also the feedback of these emissions on the natural state of the environment and back to how we arrange and plan our societies and incumbent economies. Currently, we have regular scientific and policy investigations through the United Nations Intergovernmental Panel on Climate Change (UNIPCC) and major biannual conferences on addressing climate change through the work of the UN.

Whilst conventional approaches allow for tracking environmental impacts, and even decoupling of impacts from economic and/or population growth, what we know from investigations over the last decades is that technology is often an enabler of future growth, rather than a solution of environmental problems. When we see the impacts on our environment through the IPAT (Impact = Population*Affluence*Technology) equation, we see the impacts due to population and affluence driving the major increase in emissions over time (Ehrlich and Holdren, 1971). As such, the policy debate is shifting from conventional "end-of-pipe" solutions to environmental issues to thinking through the role of consumers and the economic system that provides for the ever-increasing demands from population and affluence.

Sustainable consumption has thus been an emerging topic of sustained interest over the last decades. If population and affluence are going to increase, how can we best control our interaction with the environment? Consumers thus have a strategic role in action for the mitigation of environmental impacts. The opportunities afforded by not only addressing technology through efficiency improvements, but also through consumers as drivers of change in production systems, are large. Change may come about in several respects: conditions for product development and/or marketing strategies may change; the types of products that consumers demand may change; or trade relationships, domestically or internationally may change.

Life-cycle approaches to investigating environmental impact have emerged as a useful paradigm in which to approach the issue of sustainable consumption. Environmental life-cycle approaches are defined as covering the impacts of a material, product or activity through the processes covering the resource extraction, processing, manufacturing, usage, and disposal of the associated goods and services. As such, the way to address environmental impacts is not so much through focusing on a particular industry or technology, but on the functionality produced by a supply chain of products. This provides a way to link the activities of individuals, households and governments through supply chains to the environmental impacts in disparate industries.

Life-cycle assessment (LCA) strives to give a complete picture of the environmental impacts of products. It can claim to do so by making an exhaustive mapping of activities that are associated with using or producing a certain product, taking into consideration entire life-cycles, from raw material acquisition through to waste handling. Keeping a life-cycle perspective is pivotal in trying to understand true environmental costs and benefits, and to achieve fair and consistent comparisons between alternatives. The LCA approach presented here will offer a number of options that let the user analyze systematically the environmental impacts of their products, and to study environmental benefits if one product replaces another product.

More recently, footprint approaches have been conceptualized to denote the life-cycle impacts of a product, consumer or population. A life-cycle approach (Weidema et al., 2008; Finkbeiner, 2009) is taken implicitly in the calculation of the footprint for each item consumed by a population. Individuals, populations and other entities can hence use environmental footprints to consider their individual or collective consumption and to analyze which items of consumption embody the most environmental impact. The publication of footprint results by type of good or service is of value in helping consumers to "green" their consumption – enabling shifts from more to less environmentally intensive products. Such approaches have been well elucidated through the focus on carbon footprints (Weber and Matthews, 2008; Hertwich and Peters, 2009; Minx et al., 2009).

Whilst life-cycle approaches to calculating environmental impacts traditionally used a bottom-up or engineering basis for tracking the supply chains of production through an economy, more recently it has been appreciated that the initial development of input–output analysis (IOA) was relevant and well established in calculating the embodied impact of consumption. With a rather simple extension of the input–output (IO) system to consider inputs to production from the environment and emissions from production to the environment (Leontief, 1970), it is possible to address societal impacts on the environment, the "footprints" of consumption, in a single eloquent framework.

It is important to note here that footprints and life-cycle approaches have been almost exclusively used in a historical setting so far – they allow the allocation of production-based impacts to consumption, and thus use fixed historic technological and trade relationships. Where footprints and life-cycle approaches have been used in prospective studies, the concept of a "footprint" has not been to model how an economic system will evolve, but only to apply the same logic of allocating production-based impacts to consumption.

This chapter is structured as follows: sections 5.2 and 5.3 present the goal and history of environmental footprints; section 5.4 different indicators of environmental footprints and their policy relevance (ecological, material, water, land, carbon, etc.); in section 5.5 the methods of calculating environmental footprints are presented; and in section 5.6 a range of case studies is taken from the literature to demonstrate the utility of IO techniques in assessing environmental consequences.

5.2 GOALS AND SCOPE OF ENVIRONMENTAL FOOTPRINT APPROACHES

Footprint approaches generally have one main goal, and that is to connect consumption to the source of environmental impacts. Beyond this overarching goal, there is a range of foci within environmental footprint approaches, including assessment of consumer choices for reducing carbon footprints – focusing on lifestyle choices; providing information at the product level in order to help consumers choose low-carbon alternatives; procurement policies more generally focusing on supply chains, more integrated planning; national emissions accounting; trade and carbon leakage; and role of consumption in driving change in environmental impact.

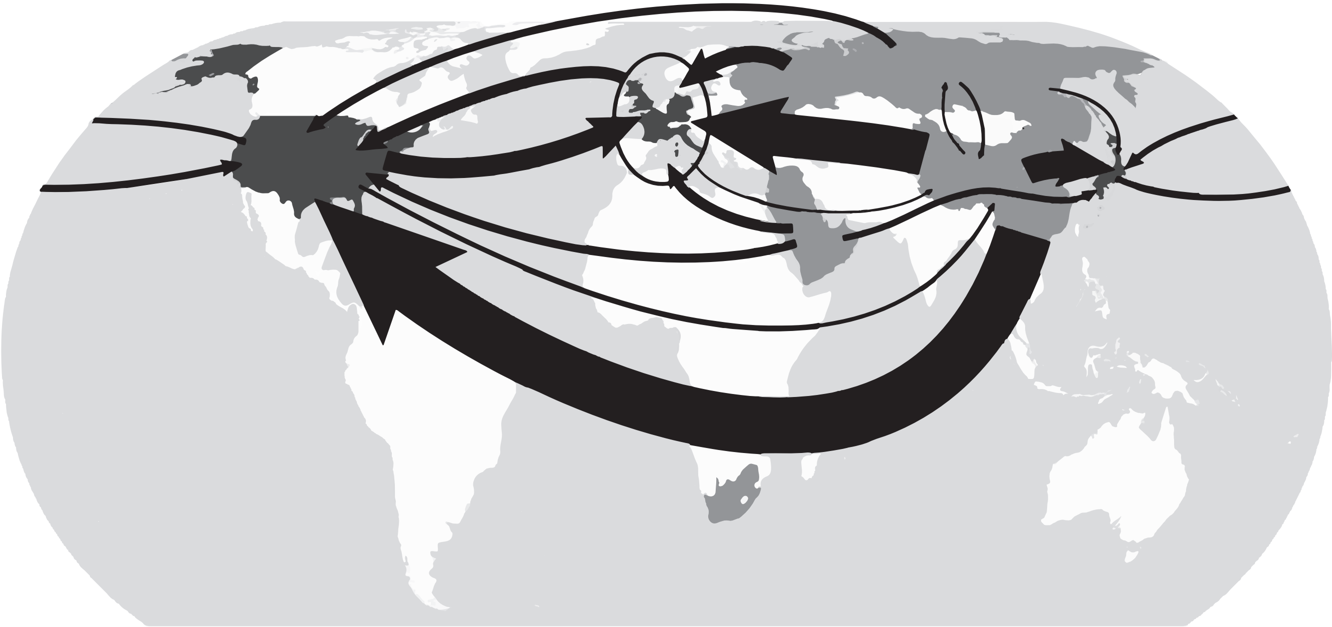
At the national level, we see the goal of environmental footprints as both a method to assess social equity in general (the relationship that globalization has on environmental and socioeconomic outcomes), and more specifically as a way to combat what is denoted as weak or strong carbon leakage. By taking a footprint approach, the goal is to reduce adverse effects at the global level, but allowing policy derivation by national actors. Footprint approaches in general are designed to circumvent problem shifting, by including a scope of assessment that is directly linked to the affluence and consumption of a population. Some seminal work has come out, particularly in the area of carbon footprints (covering all greenhouse gas emissions) since the early 2000s – giving for the first time a global perspective to the issue. By providing a footprint- or consumption-based approach, the displacement of greenhouse gas emissions through international supply chains was captured (Hertwich and Peters, 2009; Minx et al., 2009; Peters et al., 2011) – Figure 5.1. With the focus on direct and indirect emissions, and by taking a final demand perspective, the approach is very intuitive for input–output practitioners.

One key concept that is central to the footprint approach is the notion of "embodiment." The embodied impact is the impact caused in the supply chain of a product – it includes impacts that were caused during the production process of a good or service. For example, CO_2 emitted in electricity generation is said to be "embodied" in the electricity used to power a light. An "embodied" approach is central to, and synonymous with, all footprint analysis. The concept of embodied impact has been found to be useful in conceptualizing our indirect reliance on the natural systems that support us – especially as consumers become more disconnected from basic means of production.

It is important to emphasize that an embodied impact or a footprint is not a tangible quantity. It implies some sort of allocation or notion of responsibility of a tangible emission or resource use to the products or functions that are outputs of the product system. This allocation can be done by different methods (Loiseau et al., 2012; Majeau-Bettez, Wood and Strømman, 2014), and based on different characteristics (Ardente and Cellura, 2012; Weinzettel, 2012). An embodied impact is based on historical accounting relationships – it is not a measure of potential or optimal environmental impact.

5.3 HISTORY OF ENVIRONMENTAL ACCOUNTING IN INPUT–OUTPUT ANALYSIS

Input–output analysis was extended to allow quantitative analysis of environmental choices and flows in the late 1960s (see Isard et al., 1967; Daly, 1968; Ayres and Kneese, 1969; Leontief, 1970; Leontief and Ford, 1972). Various models were proposed, including integrated economic-ecological



Source: Davis and Caldeira (2010).

Figure 5.1 *Largest interregional fluxes of emissions embodied in trade (Mt CO_2 y−1) from dominant net exporting countries (medium grey) to the dominant net importing countries (dark grey). Fluxes to and from Western Europe are aggregated to include the United Kingdom, France, Germany, Switzerland, Italy, Spain, Luxembourg, the Netherlands and Sweden* representations (Isard et al., 1967), but perhaps it was Leontief (1970) who took the most useful approach, in which an open input–output framework was established in order to incorporate the forward and backward flows between the economy and the environment.

Since that time, the use of the static input–output framework has been applied extensively to environmental problems, both as an investigative tool, and as a means by which to derive policy. Regional applications (see Hewings and Jensen, 1989) were an initial focus, principally for planning objectives (Cumberland, 1966; Beyars, 1974), and resulted in a wide range of studies on levels of development (Miernyk, 1965; Hewings, 1982; Jensen, Hewings and West, 1987; Jackson, Hewings and Sonis, 1989; Hewings and Romanos, 1994; Wood and Lenzen, 2009); interregional linkages (Miernyk, 1965; Batten, 1982; Solomon and Rubin, 1985; Sonis and Hewings, 1998); and intersectoral linkages (Beyars, 1974; Holland and Cooke 1992; Hughes and Holland, 1994; Coffey, 1996). Early integration of input–output analysis with environmental processes gained significant momentum in the 1970s when the oil crises hit, and demand grew for knowledge of the interdependency of the economy on energy resources. As a result, a number of early studies looked at the energy dependency of goods and services (Herendeen, 1973; Bullard and Herendeen, 1975; Bullard, 1976; Bullard, Penner and Pilati, 1978) and industrial energy use (Giarratani, 1976).

Further development not only integrated consumption of environmental resources, but also included effects of residuals such as air pollution (see Leontief and Ford, 1972; Chatterji, 1975a, 1975b). As time passed, and with scientific knowledge concerning anthropogenic global warming growing, greater emphasis has been placed on carbon dioxide, greenhouse gas and energy studies. The basic input–output framework has been applied on numerous occasions for analyzing responsibility of energy use or emissions. Examples include sectoral responsibility for energy use in Australia (Shariful Islam and Morison, 1992); industrial energy use in the UK (Jenne and Cattell, 1983); household energy demand (Pachauri and Spreng, 2002); and the greenhouse gas emissions due to consumption patterns (Lenzen, 1998; Kim, 2002). Further applications include specific focuses on relationships between different sectors, and in the case of Machado and Miller (1997), the substitution of information for energy in economic terms. More recently the focus has been on assigning consumer responsibility for carbon emissions and other environmental impacts using the notion of life-cycle assessments or carbon and ecological footprint techniques (Bicknell et al., 1998; Hubacek and Giljum, 2003; Wiedmann et al., 2007; Wood and Garnett, 2009).

5.4 INDICATORS USED IN ENVIRONMENTAL FOOTPRINTS

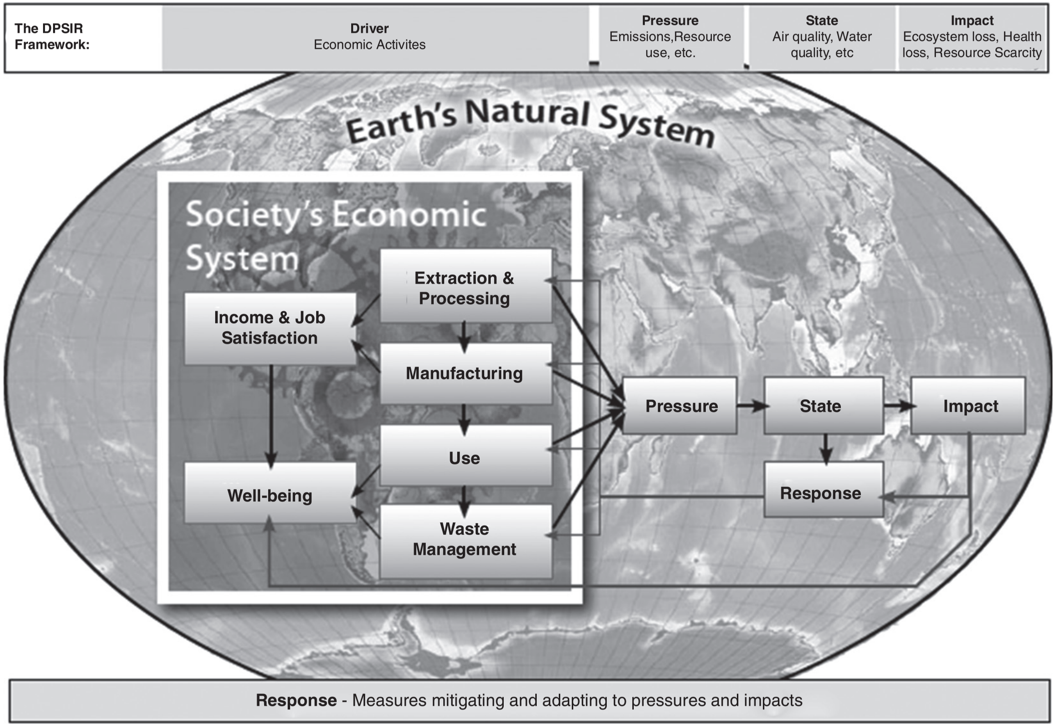
Environmental footprints cover a broad and ever-expanding array of environmental emissions, resources use and impacts. It is not the intention to cover all types of indicators in this chapter but to cover some of the main application areas. A framework to cover how the environment can be modeled is useful, however. One of the more applicable frameworks is the Drivers-Pressure-State-Impact-Response (DPSIR) framework (Figure 5.2) (Hertwich et al., 2010).

The DPSIR framework can be used as a way to link the concepts of input–output analysis, from consumption (consumption linked to income and well-being) to systems of production (extraction, processing – intermediate production), to direct requirements or pressures on the environment (air emissions, resource extraction), and further to consideration of state and hence impact measurement. Impact measurements mean that we consider the impact an emission or resource use has on the environment, for example through the characterization of air emissions in terms of global warming potentials, the characterization of land use in terms of impact on biodiversity, and so on. It is not our focus to bring in these concepts here; suffice to say that most classic environmental footprints work on the pressure level, of which there are many types of pressures acting on the environment, and a smaller but developing set of indicators work to bridge the calculation of impacts. There is a cost in moving from pressure to impact indicators, however – pressure indicators are relatively easily measured and described, whilst impact indicators invariably require modeling of temporal and spatial qualities of the environment, as well as the direct pressures.

Below, five key types of indicators are introduced – all with differing utility. All indicators can bridge between pressure and impact, but the focus is first on indicators that attempt to describe impact, before moving towards pressure indicators. We start from the indicator known as the "ecological footprint," which first attributed the term footprint to an old concept but in the process shifted focus to consumption-based accounting. Other main indicators of environmental footprints include the investigation of greenhouse gases (carbon footprint), and material, water and land footprints.

5.4.1 The Ecological Footprint

The ecological footprint deserves an introduction, as it was perhaps the first metric of embodied impact that sought to fully connect to the



Source: Hertwich et al. (2010) for UNEP.

Figure 5.2 Driver-Pressure-State-Impact-Response framework lifestyles of people. Rees (1992) first proposed it as a way to think of human appropriation of carrying capacity – instead of how big a population a certain area can support. Rees took the inverse approach to try to conceptualize just how much area it took to support a human. The concept was further developed in Wackernagel and Rees (1995), Simmons, Lewis and Barrett (2000) and Simmons, Petroeschevsky and Lowe (2000), and because of the clear connection from resource requirements to human consumption it was later developed to utilize input–output techniques (Bicknell et al., 1998; Lenzen and Murray, 2001). The ecological footprint gained popularity because of its intuitive simplicity and ease of understanding, and helped to reopen the debate on human carrying capacity in the context of global sustainability. The ecological footprint of a population was defined as the total area of land and water ecosystems required to produce their resources and to assimilate their wastes, wherever these ecosystems are located (Rees, 2001). This land area sits both within and outside the borders of the residential area and therefore the ecological footprint is an indicator for the impacts of consumption of the residents wherever the production of goods and services takes place. As such, the ecological footprint sought to give a land-based metric to the impacts of past consumption – in so doing, attempting to convert all pressures on the environment into the land area needed, indirectly or indirectly, to provide for consumption. The metric gave an easily interpretable measure – the quantity of land needed to fulfill consumption demands relative to the available quantity, within a country, or globally. The concept of the ecological footprint became a useful tool in highlighting the unsustainability of global consumption (Costanza, 2000) – so much so that since the mid-2000s the human population has been measured as "overshooting" the regenerative capacity of the earth – meaning that we are depleting the natural capital of the earth. The world average ecological footprint was just less than 3.0 global hectares per person in 2010 but as this exceeds the 1.7 global hectares per person of biocapacity available in 2010 it is considered that we are currently living beyond the available natural capital. The ecological footprint's use in policy design and planning has also been promoted (Wackernagel et al., 1997; Wackernagel and Silverstein, 2000), although its utility there is more hotly debated (Van den Bergh and Verbruggen, 1999).

Starting in the 1990s, input–output techniques were postulated as providing a possible way to link production accounts to household consumption (Bicknell et al., 1998; Simpson, Petroeschevsky and Lowe, 2000; Lenzen and Murray, 2001) using the input–output tables from national accounts to link the land area to the consumption category. Input–output-based ecological footprints are argued to be complete in that they cover the supply chains of the entire upstream economy, which ultimately enables the production of consumer items. Local technologies are normalized using yield and equivalence factors in order to relate consumption to the average productivity of all bioproductive hectares on earth. This normalization averages out the productivity of different land types (equivalence factor) and productivity in different regions (yield factor) (Borucke et al., 2013). The ecological footprint is an aggregate of five land types: cropland, grazing land, forest, fishing ground and built-up land, as well as CO_2 land – the estimated bioproductive land area required to sequester carbon emissions. The aggregation of land use with land sequestration area gives rise to some of the criticism of the ecological footprint – it aggregates different biological mechanisms into a single result, with the policy implication being that the CO_2 land drives most changes in impacts over time (Van den Bergh and Grazi, 2015).

5.4.2 Carbon Footprints

Carbon footprints have become a popular topic in the public climate change debate, drawing from the ecological footprint concept. The approach allows policy to shift from the several key sectors that make up the bulk of impact from a production perspective, to the several other key product groups that make up the bulk of impact from a consumption perspective. The approach is seen as a way to induce empowerment in a broader range of actors – from consumers choosing low-embodied-carbon products, to companies addressing their supply chain, to the ability to market low-carbon alternatives.

The carbon footprint has further been a popular tool for populations and other entities to look at the areas of their consumption that embody the most greenhouse gases (Weber and Matthews, 2008; Hertwich and Peters, 2009). The publication of footprint categories is of value in helping consumers to “green” their consumption – enabling shifts from more greenhouse gas-intensive products to less intensive products. Within a carbon footprint, a life-cycle approach (Weidema et al., 2008; Finkbeiner, 2009) is taken implicitly in the calculation of the footprint for each item consumed by a population.

Under the Greenhouse Gas Protocol Corporate Standard, greenhouse gas emissions have been classified according to “scope.” Scope 1 emissions are the emissions from an entity’s own production (direct emissions), whilst electricity emissions associated directly with production are accounted explicitly as Scope 2 greenhouse gas emissions – that is, they are the emissions generated in the production of electricity used by the industry; Scope 3 emissions as defined under the Greenhouse Gas Protocol

Corporate Standard are all "upstream" or embodied emissions in an entity's inputs/consumption excluding its own emissions from production (Scope 1) and its own electricity consumption (Scope 2).

The greenhouse gas emission accounts used in calculating carbon footprints are fairly standard across all applications, but do have substantial room for variability in the detail. The IPCC publishes global warming potentials of different gases that have warming effects – the main three gases that are usually included in carbon footprint calculations include carbon dioxide, methane and nitrous oxide. Whilst other air emissions also have a warming effect, data uncertainty increases greatly. Greenhouse gas emission inventories are rarely constructed in a manner compatible with an input–output table (IOT) economic sector classification (Marland, 2008), and thus require further allocation from greenhouse gas-emitting activity to the economic sector producing it.

In terms of coverage of emissions, fuel combustion carbon dioxide emissions are most simply included, but most models now extend this to include industrial process emissions, solvents and other product use. Agricultural and waste emissions are also often included, whilst land use change and forestry emissions are generally not included due to the difficulty of establishing cause-and-effect mechanisms in an IO framework.

Handling of direct cross-border flows has also been problematic in tracking energy statistics in a region versus the residential uses. Some of these cross-border flows relate to the impact of purchasers by residents abroad (particularly regarding motor vehicle transit), whilst other flows relate to the extent that international transport activities are included, especially regarding the bunkering of fuels. Direct consistency with the System of National Accounts (United Nations Statistics Division, 1993) would help here, and efforts are made under the System of Environment-Economic Accounting (United Nations et al., 2014) but currently there is a lack of data in this convention, with most energy (and hence fuel combustion emissions) organized according to energy balances (International Energy Agency, 2012).

5.4.3 Material Footprints

Material footprints use the analysis of resources through an economy as a measure of "social metabolism," and gained momentum from the early 1990s with the ConAccount research network (Bringezu et al., 1997; Kleijn et al., 1999), followed by the World Resource Institute cross-country studies (Adriaanse et al., 1997; Matthews et al., 2000). Material footprints have become popular as a key indicator of resource efficiency, or resource productivity (European Commission, 2011; Eurostat, 2012; Wiedmann et al., 2013).

Material footprints seek to aggregate resources required for economies to operate, and generally aggregate through mass terms. A number of definitions are applicable to material flow analysis. Domestic extraction (DE) and direct material consumption (DMC) are calculated directly from production, import and export statistics (as defined in Weisz et al., 2007). Domestic extraction is the mass of material entering the economic system without including any unused extractions (domestic or imported) or the flows associated with imports. In comparison, DMC is the actual material consumption of the population, including the weight of imports and excluding exports. To include the embodied impact of the resources that flow across a border, the definition of raw material equivalents (RME) was developed to capture the embodied material requirements of all products, thus allowing the calculation of raw material consumption (RMC), which is in line with the footprint concept as explained across other environmental domains, and includes all upstream material requirements in the products consumed by a population, thus allocating material requirements embodied in exports to the consuming population. A final indicator, total material requirements (TMR) is defined as the summation of all material flows required for a population (Eurostat, 2001). This then includes material that enters the economic realm as well as "unused" flows – which are the necessary displacement of material for an auxiliary purpose (e.g., the creation of tailings associated with mining). Estimations of unused flows are important for three reasons. First, in a macro-sense they define the physical "overhead" of an economic system, which in many circumstances characterizes an economy's sophistication with regard to how efficient it can process its resources. Second, the unused flows in farming are important ecologically as the soil erosion component impacts negatively on long-term sustainability. Third, for mining, high levels of material flow often reflect declining ore grades and increasing requirements for mine rehabilitation services once the core product has been extracted.

Such accounting for material flows allows for the resource productivities to be calculated – looking at the total material requirements per unit value added (Wiedmann et al., 2013). Most studies have focused on the material footprints of nations taking the macro-level perspective (Weinzettel and Kovanda, 2011; Wiebe et al., 2012; Schoer et al., 2013; Wiedmann et al., 2013), albeit some studies have focused on particular material types (Weinzettel and Kovanda, 2011), and some on policies for specific sectors (Wiebe et al., 2011).

RME and material footprints have been calculated by two main approaches – using life-cycle inventory-type data to calculate the RME factors directly, thus maintaining the link to the physical quantity of a traded good (Schoer et al., 2013), or by input–output analysis – generally using monetary data on demand to implicitly calculate the full upstream material impact of that demand. Some hybrid methods have been applied, where some rows of the input–output table have physical values instead of monetary values, thus allowing a clearer link to physical statistics for some imported commodities (Schoer et al., 2013).

5.4.4 Water Footprints

Similar approaches have been applied to the concept of water footprints – often termed the "virtual trade" of water flows (Zhan-Ming and Chen, 2013). Consumption-based accounting for water has been promoted to apply better options for management of the resource – connecting disparate demands across global systems of agricultural production and consumption (Yang, Pfister and Bhaduri, 2013). Most consumers are clearly not aware at all of the vast quantities of agricultural water used in producing food products (Mekonnen and Hoekstra, 2012). One of the chief challenges of water footprints has been the need to quantify impact-related measurements, rather than volume-related measurements to the water footprint. One of the early distinctions has been on water quality, distinguishing "blue," "green" and "grey" water. Green water refers to rainwater, blue water to water extracted from the ground or surface, and grey water to polluted water (Mekonnen and Hoekstra, 2011). However, clearly, taking into account the stress that water extraction places on the environment is of key importance, and as such, the use of water scarcity impacts has become prevalent (Lenzen et al., 2013). Feng et al. (2014) argue that "using the water footprint as a policy tool to alleviate water shortage may only work when water scarcity is taken into account and virtual water flows from water-poor regions are identified." Because of the increased global trade of agricultural goods, many countries have significantly externalized their water footprints (Steen-Olsen et al., 2012). Given the ongoing shift to the industrial farming system and the increases in meat consumption the use of the water footprint will become only more important.

5.4.5 Land Footprints

To complement carbon, material and water footprints, physical land area (compared to productivity weighted land area as used in the ecological footprint) is also used in many studies (Steen-Olsen et al., 2012; Weinzettel et al., 2013; Tukker et al., 2014). Again, the concept developed from viewing land as a type of natural capital that provides inputs to production – particularly agriculture production. Land-based metrics have been connected to human appropriation of net primary productivity (Haberl et al., 2007, 2009; Erb et al., 2009), and more broadly to biodiversity impacts (Lenzen et al., 2012).

5.5 METHODS

Methodological frameworks in which to calculate environmental footprints have been established for a long time. Footprint analysis aims to quantify all direct and indirect (embodied) environmental pressures caused by a certain population, product group, or functional activity. Because of the relationship to calculation of demand-based impacts, the input–output model developed by Leontief fits the methodological requirements well. The completeness of the input–output framework, allowing for a detailed depiction at the macro-level of activities throughout the economy, and the ability to assess both direct and indirect (supply chain) environmental pressures, has seen the utility of input–output techniques been taken up by researchers and practitioners.

The nomenclature of the equations used in this chapter follows the following conventions, as shown in Table 5.1.

In a single region model, final demand y includes net exports, such that $y = y^{rr} + \sum_s z^{rs}$.

Table 5.1 Equation nomenclature

Description	Symbol	Type
Input–output coefficients matrix	A	Exogenous
Leontief inverse	B	Endogenous
Final demand (incl. net trade)	y	Exogenous
Final demand by region of production *r* and consumption *s*	y^{rs}	Exogenous
Exports (bilateral by region)	z^{rs}	Exogenous
Gross output	x	Endogenous
Factor production	F	Exogenous
Factor production final demand	f	Exogenous
Factor production coefficients	S	Endogenous
Footprint accounts	D	Endogenous
Impact accounts	H	Endogenous
Multipliers	Q	Endogenous
Region indices	r, s	Indices
Product row	i	Index
Product column	j	Index

5.5.1 Environmental Extension of the Basic Input–Output Framework

The basic input–output framework describes the transactions in the economy: the interindustry flow matrix showing the purchases of products in order to produce other products or the separate use and make tables; the factor input table F showing the primary inputs to production; and the final demand vector y showing the consumption of products by categories of final demand. From the interindustry flows the coefficient or direct requirements matrix A can be calculated as described in Chapter 4 of this *Handbook*. The interpretation is that characteristic element a_{ij} shows how much of product i is required to make a unit of product j.

The demand side equation commonly used in calculating environmental footprints is:

$$x = Ax + y. \tag{5.1}$$

For a certain demand y in a certain country, the production x required to satisfy the demand is calculated by solving equation (5.1),

$$x = By, \tag{5.2}$$

where $B = (I - A)^{-1}$ is the Leontief inverse.

The input–output framework is extended for environmental pressures by showing the primary resource requirements or emissions for each industry. The environmental inputs or wastes/emissions are hence treated much the same as labor and capital in the input–output framework. The input–output then provides the linking of environmental pressure data (e.g., emissions of greenhouse gases by an industry) for all economic sectors in an economy with the financial transactions between these sectors (intermediate demand) and thus allows for the tracing, and subsequent allocation of the environmental pressures to the final consumption of product groups (Leontief, 1970).

Analogous to the factor inputs are environmental inputs or emissions to the environment. The factor input table is replaced by or extended to a “stressor” or “environmental intervention” matrix F, of environmental factors by industries dimension. Similar to the basic input–output coefficients, environmental factors per unit production are derived according to $S = F\hat{x}^{-1}$ (where ^ places a vector on the diagonal of a matrix) or one of the models described in Chapter 4 of this *Handbook*. Depending on the type of environmental impact being investigated, the generalization of the input–output matrix to include environmental inputs can be quite a simple allocation of environmental statistical data to corresponding industries, to quite complex modeling required on allocating single-activity data to multiple industries/consumers (such as emissions resulting from road transport).

In order to calculate environmental footprint D due to final demand, we utilize the Leontief inverse as per standard input–output analysis and include direct environmental impacts from households f (a vector with one component for each environmental factor, featuring, for example, emissions from wood fires in the home):

$$D = SBy + f. \tag{5.3}$$

The environmental footprint is a vector with one component for each environmental factor, capitalized in anticipation of disaggregation by region.

5.5.2 Life-Cycle Approaches

The life-cycle concept grew out of the need to assess environmental impacts stemming from all stages of a product's life, including from resource extraction, processing, manufacturing, distribution, use and disposal. Footprint calculations employing the life-cycle approach are often done in different ways: two main approaches are through life-cycle inventory/coefficient-based approaches, and through the use of input–output models. The approaches are not necessarily mutually exclusive (hybrid approaches combining the two also exist), but in practice, often use distinct data sources and system boundaries (see Weinzettel et al., 2014). It can be argued that environmental footprints are necessary by-products or outcomes of any LCA (Weidema et al., 2008), and as such, significant effort has been made by umbrella organizations to formalize standards (e.g., stemming from ISO 14040 and 14044) on the carbon footprint of products. Whilst the approaches stemming from the life-cycle community provide significant impetuous for the uptake of environmental footprint approaches, we necessarily focus this chapter on the utility and focal area of input–output-based approaches. Given the same computational structural and basic data requirements of IOA and LCA (Heijungs and Suh, 2002), there is a clear overlap of possibilities.

In life-cycle-based methods, impacts embodied in consumption are estimated based on "inventory" data that include the required inputs used to produce a kg or € of a good. As such, inventory data in LCA can be organized the same way as in input–output analysis (Heijungs, 1997). Inventory data cover technologies used to produce a good, and either correspond to functional processes that aggregate upstream supply chains (so-called system processes – corresponding to input–output multipliers), or technology-level coefficients (unit processes – corresponding to input–output coefficients), and can be just as easily arranged in a matrix format (Heijungs and Suh, 2002). Life-cycle approaches operating at the unit process level use the same linking of data as input–output analysis in order to produce what are known in LCA as system processes and in IO as multipliers Q to calculate the environmental impact per unit of product consumed, or the "embodied impact" of a product:

$$Q = SB. \tag{5.4}$$

5.5.3 Characterizing Environmental Pressures into Environmental Impacts

An additional point of departure from classic generalized input–output analysis returns us to the discussion of the DPSIR framework and the link between environmental pressures and impacts. A classic generalization of input–output tables tracks substances/resources used by, or emitted by, industries. In common with life-cycle assessment practice, it is now becoming common to apply a matrix of characterization C of the substances in order to talk about environmental requirements in terms of environmental impacts – here denoted as matrix of environmental impacts H due to the final demand y:

$$H = CSBy. \tag{5.5}$$

In material flow accounting, the characterization is a simple sum of all physical inputs into the economy. In greenhouse gas accounting, it is the application of global warming potentials to individual emissions to air in order to estimate the climate impact or temperature response. In land and water accounting, practices vary from simple summation of land use and water extractions to characterization based on productivity measures, land availability or water scarcity.

5.5.4 Multiregional Input–Output Analysis

Thus far, trade has not been explicitly considered. Historically, and for simplification, generalized input–output analysis has either excluded imports from the system boundary, or as full supply chains have come into focus, frequently assumed domestic and import production to employ the same technology ("domestic technology" or "single-region" assumption). Such analysis assumes identical environmental and technological coefficients domestically as abroad, and allows the analysis to be performed based only on national input–output tables and environmental accounts (see Wiedmann et al., 2007).

To include the global aspect of supply chains requires the inclusion of pressures occurring worldwide in enabling the production of the goods and services in multiple regions, which are finally consumed within a certain territory. Multiregional input–output (MRIO) methods seek to address the issues by linking together all regions of the globe in a bilateral context – tracking the imports and exports of products between industries in different regions. MRIO methods cover full supply chains, following the flow of goods and services all the way from extracted resource in a region to the final consumption of a product in other regions. In the derivation that follows, it must be remembered that environmental footprints are used to look at the impacts of current (or past) consumption, and as such, as well as using fixed technological coefficients (defined in the A matrix above when solved as a system of linear equations with the Leontief inverse), trade relationships are also fixed based on observed trade flows. The derivation follows, and further discussion on generalization of modeling optimal scenarios is included in subsection 5.5.7.

To begin, we introduce the regional dimension to the matrices: denoting a certain region r, and other regions s, equation (5.1) can be rewritten for region r as the output x produced in order to satisfy intermediate demand $A^{rr}x^r$ in region r as well as final demand of consumers in that region y^{rr} and observed exports to all other regions $\sum_s z^{rs}$ (given that a component of final demand is the exports from the producing country; that is, $y = y^{rr} + \sum_s z^{rs}$):

$$x^r = A^{rr}x^r + y^{rr} + \sum_s z^{rs}. \tag{5.6}$$

In a two-region model (with regions r and s), this can be written in matrix form as:

$$\begin{pmatrix} x^r \\ x^s \end{pmatrix} = \begin{pmatrix} A^{rr} & 0 \\ 0 & A^{ss} \end{pmatrix} \begin{pmatrix} x^r \\ x^s \end{pmatrix} + \begin{pmatrix} y^{rr} + z^{rs} \\ z^{sr} + y^{ss} \end{pmatrix}. \tag{5.7}$$

The observed exports from region r to region s are summarily the imports from region s to region r, which can be broken down into observed imports to intermediate production Z^{sr} and imports to final demand y^{sr}, assuming that these data are available, which it commonly is:

$$z^{rs} = z^{rs}e + y^{rs}, \tag{5.8}$$

where e is a summation vector (all entries one). Or, normalizing by domestic production, $A^{rs} = z^{rs}\widehat{x^{s}}^{-1}$:

$$z^{rs} = A^{rs}x^{s} + y^{rs}. \tag{5.9}$$

And inserting into equation (5.7),

$$\begin{pmatrix} x^{r} \\ x^{s} \end{pmatrix} = \begin{pmatrix} A^{rr} & A^{rs} \\ A^{sr} & A^{ss} \end{pmatrix} \begin{pmatrix} x^{r} \\ x^{s} \end{pmatrix} + \begin{pmatrix} y^{rr} + y^{rs} \\ y^{sr} + y^{ss} \end{pmatrix}, \tag{5.10}$$

with A^{rs} showing the technical coefficients of imported intermediate demand in region s from regions r, and A^{rr} and A^{ss} showing the domestic intermediate coefficients of each region. We may then continue as per the basic input–output framework equations (5.2) and (5.3).

Solving for x,

$$\begin{pmatrix} x^{r} \\ x^{s} \end{pmatrix} = \begin{pmatrix} B^{rr} & B^{rs} \\ B^{sr} & B^{ss} \end{pmatrix} \begin{pmatrix} y^{rr} + y^{r} \\ y^{sr} + y^{ss} \end{pmatrix}, \tag{5.11}$$

where $\begin{pmatrix} B^{rr} & B^{rs} \\ B^{sr} & B^{ss} \end{pmatrix}$ is the Leontief inverse of $\begin{pmatrix} A^{rr} & A^{rs} \\ A^{sr} & A^{ss} \end{pmatrix}$.

Using the Leontief inverse implicitly assumes fixed trade relationships (i.e., non-competitive imports), much as a linear production function is assumed in a single-region model. Generalizing the two-region model for environmental inputs, we calculate the environmental account by normalizing environmental pressures F^{r} by gross output x^{r} to give environmental intensities $s^{r} = F^{r}\widehat{x^{r}}^{-1}$. Impacts of consumption are $D^{r} = S^{r}x^{r}$ or, for the two regions simultaneously, substituting equation (5.11),

$$\begin{pmatrix} D^{r} \\ D^{s} \end{pmatrix} = \begin{pmatrix} S^{r} & 0 \\ 0 & S^{s} \end{pmatrix} \begin{pmatrix} B^{rr} & B^{rs} \\ B^{sr} & B^{ss} \end{pmatrix} + \begin{pmatrix} y^{rr} + y^{rs} \\ y^{sr} + y^{ss} \end{pmatrix}. \tag{5.12}$$

These impacts can be disaggregated by regional source of consumption,

$$\begin{pmatrix} D^{rr} & D^{rs} \\ D^{rs} & D^{ss} \end{pmatrix} = \begin{pmatrix} S^{r} & 0 \\ 0 & S^{s} \end{pmatrix} \begin{pmatrix} B^{rr} & B^{rs} \\ B^{sr} & B^{ss} \end{pmatrix} + \begin{pmatrix} y^{rr} & y^{rs} \\ y^{sr} & y^{ss} \end{pmatrix}. \tag{5.13}$$

The meaning of the variables in equations (5.12) and (5.13) is as follows: $D^{r} = D^{rr} + D^{rs}$ is the environmental pressure on the domestic territory r due to consumption in region r and consumption in region s; whilst $D^{rr} + D^{sr}$ is the environmental pressure from consumption in region r, due to production in both region r and region s. $D^{rr} + D^{sr}$ is otherwise known as the environmental footprint – the total embodied impact in the consumption of region r, no matter where the production processes take place.

The multipliers used in MRIO analysis cover all monetary goods and services, as per equation (5.4):

$$\begin{pmatrix} Q^r \\ Q^s \end{pmatrix} = \begin{pmatrix} S^r & 0 \\ 0 & S^s \end{pmatrix} \begin{pmatrix} B^{rr} & B^{rs} \\ B^{sr} & B^{ss} \end{pmatrix}. \tag{5.14}$$

MRIO approaches cover the system boundary of the economy – any valued good and service is included. As the data requirements of describing industrial production (S^r for environmental or other factor inputs and A^{rs} for inputs of processed goods and services) are substantial, the tractability of data becomes more difficult, and products are always aggregated into broader product groups.

In national accounting frameworks, single-region models have often been used due to estimating the environmental footprint of trade under simplifying assumptions of domestic technology applied to imports (Wood and Dey, 2009; Tukker et al., 2014), for example:

$$\begin{pmatrix} D^{rr} & D^{rs} \\ D^{sr} & D^{ss} \end{pmatrix} = \begin{pmatrix} S^r & 0 \\ 0 & S^s \end{pmatrix} \begin{pmatrix} B^{rr} + B^{sr} & 0 \\ 0 & B^{rr} + B^{sr} \end{pmatrix} + \begin{pmatrix} y^{rr} & y^{rs} \\ y^{sr} & 0 \end{pmatrix}. \tag{5.15}$$

It should be noted, however, that the domestic technology assumption is highly restrictive, and can introduce considerable error into environmental footprints analysis especially for highly open economies (Andrew et al., 2009; Hertwich and Peters, 2009).

5.5.5 Impacts Embodied in Trade

In order to look at the embodied impact of trade flows, multipliers have been applied to bilateral trade data. This implies embodied impacts in monetary exports z^{rs} and monetary imports z^{sr} include double counting of all goods that are traded in intermediate consumption (Peters, 2008), hence giving impacts embodied in exports as $D^r_{\text{exp}} = Q^r \sum_s z^{rs}$, and impacts embodied in imports as $D^r_{\text{imp}} = \sum_s Q_s z^{sr}$.

5.5.6 Bilateral Trade Methods

In multiregional methods, observed intermediate trade is endogenized in the intermediate flow matrix. Trade treated exogenously, as per single-region input–output models – has given rise to bilateral trade approaches (Peters, 2008; Peters et al., 2011) in order to align domestic footprints in bilateral trade data. The representation of the input–output system then derives from equation (5.7).

Impacts embodied in inter- or intraregional trade are then calculated with bilateral trade data z^{rs} as per:

$$D^{rs} = S^{r}B^{rr}z^{rs}. \tag{5.16}$$

Summation over importers gives pollution embodied in exports, $D^{r}_{\text{exp}} = \sum_{s} D^{rs}$. Summation over exporters gives pollution embodied in imports, $D^{r}_{\text{imp}} = \sum_{s} D^{sr}$. Carbon leakage can be defined as the emissions from non-Annex I countries (those under the Kyoto Protocol without emissions constraints; Peters, 2008): $D^{r}_{\text{CL}} = \sum_{s \notin I} D^{sr}$.

5.5.7 Historic Analysis versus Modeling: Fixed Production and Trade Coefficients

Finally, it should be noted that the allocation of environmental impact to final demand is done in an analytical rather than modeling framework. By analytical, it is meant that past historical input–output tables are analyzed with respect to the allocation of impacts along observed global supply chains. This implies fixed production structures and fixed trade relationships in the allocation of environmental impact to the consumer. In contrast, modeling (or forward-looking) frameworks may be applied to estimate economic structure and future environmental emissions via a range of econometric or optimization approaches (see an introduction to such techniques in Ten Raa, 2006). Some modeling approaches look at fixed input (technological) structures, but allow for the reallocation of production due to changing trade relationships (Duchin, 2005; Ten Raa and Shestalova, 2014). For example, as it is cleaner to produce aluminum in countries with low-carbon electricity supplies (e.g., hydropower in Norway), an optimum arrangement of global trade could see increased export of aluminum from such countries if the current situation is sub-optimal, or if global emission caps are tightened or prices are applied to greenhouse gas emissions. Other types of modeling (including general equilibrium, and most econometric models) look at changing input (technological) coefficients as well as, or instead of, changing trade relationships (Moses, 1960; Noll and Trijonis, 1971). Such models seek to capture, for example, the response to prices that consumers will have to a carbon tax. There is a connection between the changes in the input coefficients and the trade flows on the one hand, and the performance of the economy on the other, but it is not obvious (Ten Raa and Mohnen, 2002). Some efforts have begun to link both modeling and analytical approaches in the calculation of environmental footprints, where modeling approaches are used to calculate scenarios of economic relationships, and analytical approaches are used to investigate the supply chain relationships between production and consumption approaches used in environmental footprint approaches (Turner et al., 2012).

5.5.8 Aggregation Error in Footprint Analysis

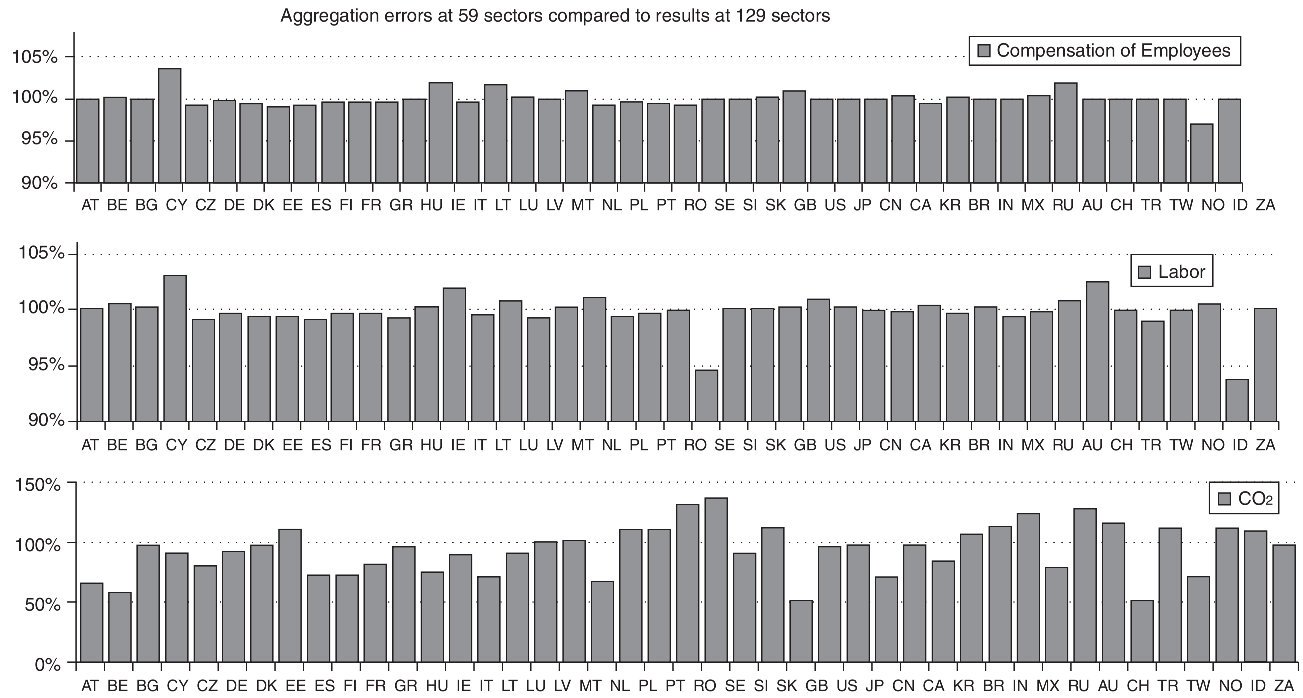
As a final methodological note, it is interesting to think about what types of data are necessary in order to accurately employ input–output methods for footprints analysis. It can be argued that, of prime importance, the resolution of data underpins the accuracy of results and policy options that can be derived from input–output footprint analysis. From an economic viewpoint, it is often regional disaggregation that is desired, as products and industries are often disaggregated in a way that seeks to provide adequate resolution on value added or other variables of interest. In comparison, for environmental issues different types of resolution are required – greenhouse gas emissions are perhaps the most evenly distributed across industries, but land use, water use and impacts associated with resources are necessarily often grouped together in few industries. This begs the question of just how much aggregation error is introduced when following specific supply chains in environmentally extended input–output analysis.

Bouwmeester and Oosterhaven (2013) analyze the issue for carbon dioxide and water – finding sectoral and regional aggregation particularly sensitive for water. Similarly, Stadler, Wood and Steen-Olsen (2014) investigate sensitivity of technological data for three different indicators – again showing the higher errors associated with land indicators compared to both greenhouse gas emissions and employment. Wood et al. (2014) analyze variation across intensities and multipliers of disaggregated tables from the EXIOBASE project, and the impact for overall footprint calculations (Figure 5.3).

Lenzen (2011) explores the issue more generically for environmental impacts – running a range of sensitivity analyses to establish whether it is better to aggregate environmental impacts to economic classifications, or disaggregate economic classifications to the level of detail of environmental impacts, finding that the latter is always preferred.

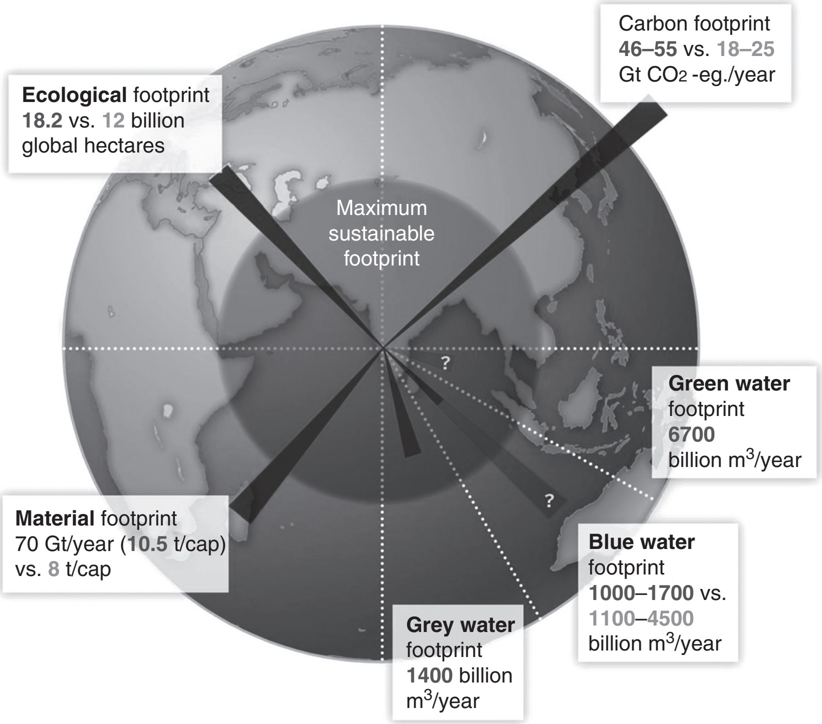
5.6 CASE STUDIES

A range of different scales of analysis exists for which environmental footprints are produced, each with their own implications for specific policy. Globally, the concept of a footprint (consumption-based impact) is equivalent to the concept of a production-based environmental pressure. That is, at a global level, the total impact is the same, and can be interpreted more as a reference to a planetary boundary for a certain impact type (Figure 5.4; Hoekstra and Wiedmann, 2014).



Source: Wood et al. (2014).

Figure 5.3 Variation in export accounts from impacts embodied in trade – compensation of employees, labor and carbon dioxide (CO_2)



Source: Hoekstra and Wiedmann (2014).

Figure 5.4 Total global impacts of different footprints

5.6.1 Countries

More insightful from an input–output perspective is the focus of environmental footprints at the national scale. The original notion of a footprint was to capture the sustainability of a population at the national scale, and it has perhaps been the most prevalent area in recent studies. Central to country-level assessments is the handling of trade, and the environmental impacts embodied in the goods and services imported and exported from respective countries. Of particular interest is how these trade relationships have changed over time, so that the trends towards globalization can be interpreted with respect to environmental impacts.

From equation 5.13, we can calculate the impacts embodied in final demand of a certain region. Where the environmental pressure from consumption in region *r* from production in both region *r* and all other regions *s* is equivalent to the environmental footprint of region *r*.

A growing number of studies are coming out at the country level – both single studies and multiregional studies. The availability of large global multiregional databases (Table 5.2) has greatly facilitated the possibilities of undertaking this work. A key point is the ability to estimate the change in an environmental metric when going from a production-based approach to a footprint or consumption-based approach, by explicitly addressing the embodied impacts of trade. The studies thus allow for a different perspective to be taken from the traditional environmental metrics of a country. Does it really benefit the environment if environmental impacts occur outside the country border? Such studies generally show that wealthy countries have outsourced much of their environmentally intensive industry (often associated with low wage rates) such that their environmental footprints are larger than their production accounts.

Of particular interest in country-level studies are developments over time. Just as international climate agreements have focused on reductions relative to a baseline year, footprint studies have been able to show a complementary perspective on whether this has been achieved from a consumption perspective, which is more closely aligned with the livelihood of a population. One of the first studies for the UK over a time series of ten years showed a statistically different divergence in results when looking at greenhouse gas emissions from a production-based perspective (emissions reduced in the UK territory) to a consumption-based perspective (Figure 5.5) (Wiedmann et al., 2010; Lenzen, Wood, and Wiedmann, 2010) given calculations based on historical input–output and trade data.

An example of resource footprints across carbon, land, material and water is presented in Figure 5.6 for 2007 using the EXIOBASE v2.3 database (Wood et al., 2015). EXIOBASE is a full multiregional input–output model. The source of the monetary data on consumption is the individual country input–output tables, coupled with the bilateral trade data processed to match the individual country input–output tables whilst maintaining trade balances.

Based on the EXIOBASE MRIO, comparisons between production- and consumption-based accounts are readily available. The production-based indicators account for the environmental pressures within the geographical bounds of a region or country. On the other hand, the footprint, consumption-based indicators represent the direct and indirect pressures caused by the final demand in a specific country or region.

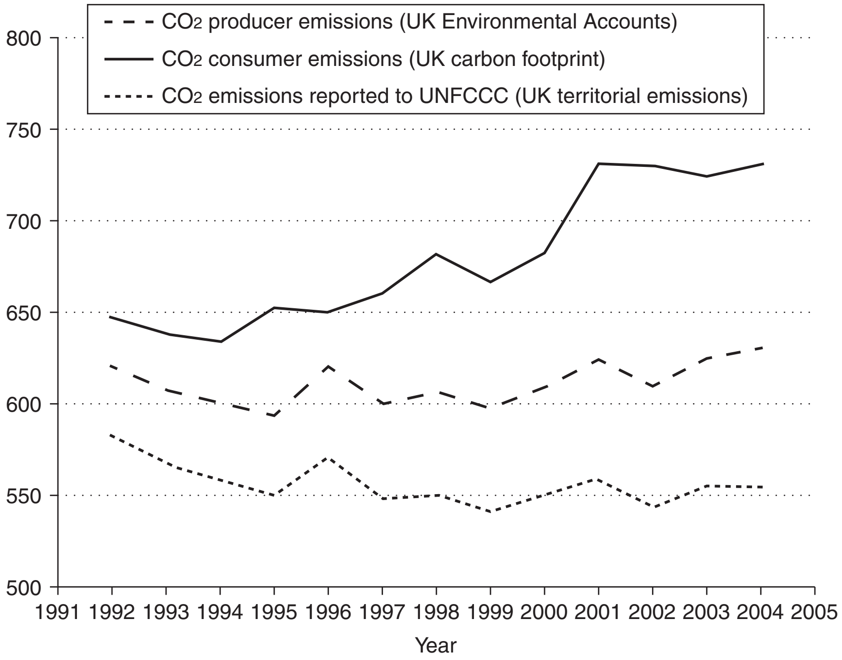
The main trend is that environmental pressure per capita is strongly linked to affluence, with wealthy countries dominating the top positions in the chart, generally for most environmental pressures, but especially for

Table 5.2 Overview of currently available MRIO databases

Database Name	Countries	Type	Detail ($i \times p$)*	Time	Extensions	Approach
Eora	World (around 150)	MR SUT/ IOT	Variable (20–500)	1990–2009	Various	Create initial estimate; gather all data in original formats; formulate constraints; detect and judge inconsistencies; let routine calculate global MR SUT/IOT
EXIOPOL	World (43 + RoW)	MR SUT	129 × 129	2000**	30 emissions, 60 IEA energy carriers, water, land, 80 resources	Create SUTs; split use into domestic and imported use; detail and harmonize SUTs; use trade shares to estimate implicit exports; confront with exports in SUT; RAS out differences; add extensions
WIOD	World (40 + RoW)	MR SUT	35 × 59	1995–2009, annually	Detailed socioeconomic and environmental satellite accounts	Harmonize SUTs; create bilateral trade database for goods and services; adopt import shares to split use into domestic and imported use; trade information for RoW is used to reconcile bilateral trade shares; add extensions
GTAP-MRIO	World (129)	MR IOT	57 × 57	1990, 1992, 1995, 1997, 2001, 2004, 2007	Five (GWP), land use (18 AEZ), energy volumes, migration	Harmonize trade; use IOTs to link trade sets; IOT balanced with trade and macroeconomic data
GRAM	World (40)	MR IOT	48 × 48	2000, 2004	Various	Use harmonized OECD IOTs; neglect differences like $i \times i$ and $p \times p$; use OECD bilateral trade database to trade link
IDE-JETRO	Asia-Pacific (8: 1975) (10: 1985–2005)	MR IOT	56 × 56 (1975) 78 × 78 (1985–1995), 76 × 76 (2000, 2005)	1975–2005	Employment matrices (2000, 2005)	Harmonize IOTs based on cross-country survey information; link via trade, manual balancing to reduce discrepancies within a certain bounds

Note: *I = number of industries; p = number of products; **the follow-up project CREEA constructs the EE GMRIO for 2007; AEZ = Agro-ecological zone; GWP = global warming potentials; IOT = input–output table; MR = multiregional; SUT = supply and use table.

Source: Tukker and Dietzenbacher (2013).



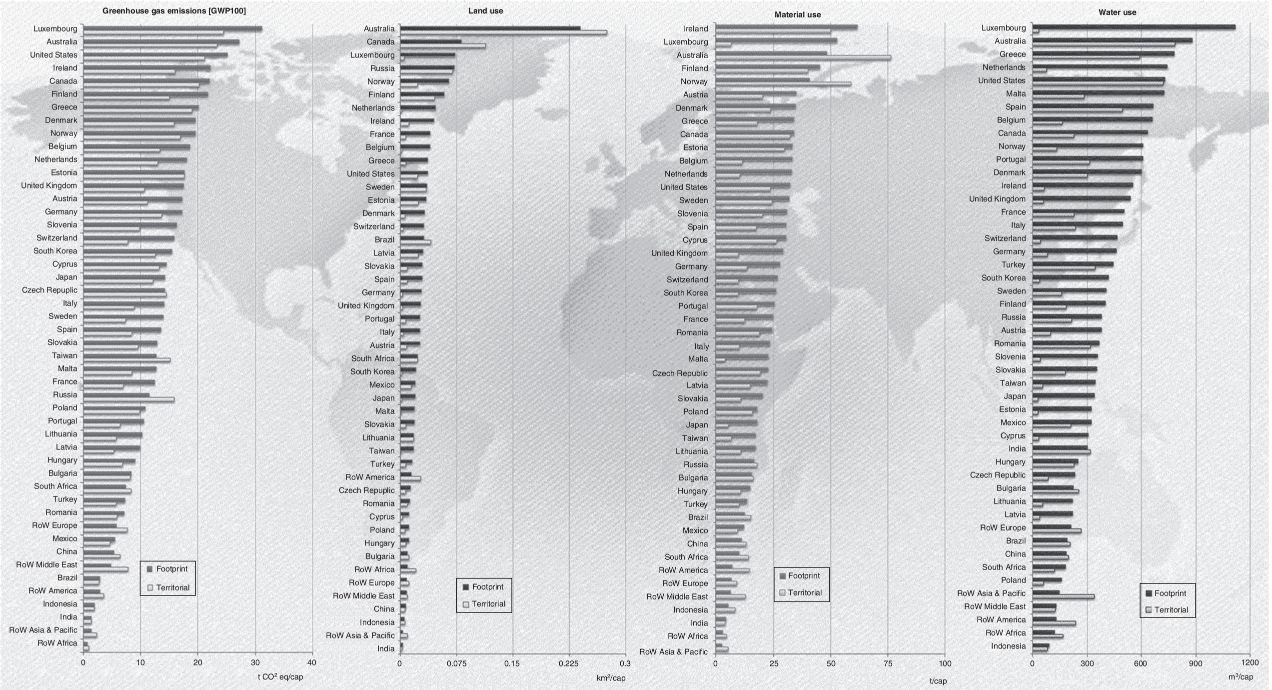
Note: UNFCCC = United Nations Framework Convention on Climate Change.

Source: Wiedmann et al. (2010).

Figure 5.5 Estimates of emissions according to territorial and consumption approaches for the UK

greenhouse gas emissions and material use. Wealthy countries are generally also net importers of embodied environmental pressures, having a larger footprint than a pressure on the domestic territory. Poorer countries generally show the opposite – developing countries and regions dominate the lower positions in the ranking, and are net exporters of environmental pressure.

Across the indicators, we see a large variation of territorial impacts for different countries in similar levels of affluence. Whilst territorial carbon emissions are often higher for wealthier countries, the territorial impacts on local resources – land and water – have a much stronger relationship to the endowment of the resource in each country. This is the principle argument around globalization, and also around why footprint measures are relevant. Trade helps countries with large endowments of factors of production to use these resources to provide goods and services for those countries without such access to resources.



Source: Own calculations updating results from Tukker et al. (2014).

Figure 5.6 Results from the EXIOBASE v2.3 database on resource footprints across greenhouse gas emissions, land use, material use and water use – territorial vs footprint approach

5.6.2 Trade

Delving deeper into the issues surrounding how embodied impacts are included in the assessment of observed trade, there are two complementary perspectives: (1) the net trade in footprint indicators between several regions (as investigated above – showing the difference between consumption and production perspectives); and (2) the (bilateral) trade flows between the regions. For the assessment of impacts embodied in trade flows, two approaches are available: the MRIO approach applied to trade, or the bilateral trade approach (see section 5.5).

In multiregional methods, intermediate trade is endogenized in the intermediate flow matrix, hence double counting of all goods that are traded in intermediate consumption (Peters, 2008). In the bilateral trade approach, intermediate trade is kept exogenous so as to assess impacts associated with total trade without including the same trade flows in the supply chain. Impacts embodied in inter- or intraregional trade are then calculated with bilateral trade data as per equation (5.16).

Emissions embodied in bilateral trade (EEBT) approaches can be summarized as capturing the direct and indirect domestic emissions for total trade. The point of departure from MRIO is that it is only domestic emissions that are captured, as opposed to the full upstream emissions. The application thus to trade data allows the emissions multipliers to be consistent with the bilateral trade data. Table 5.3 shows a comparison of properties of MRIO vs EEBT approaches from Peters (2008).

In Tables 5.4 and 5.5, the results are presented for the EU-27 trade flows for the year 2000 based on the first version of EXIOBASE (Tukker et al., 2013; Wood et al., 2014).

Comparison of results shows a clear difference to the level of manufacturing of products, EEBT approaches – directly aligned with trade statistics count emissions directly associated with exports higher than highly manufactured products with larger supply chain emissions. Of note is the high emissions embodied in the exports of chemicals and machinery/equipment – these product groups are the ones where we see supply chain emissions also in products imported to the EU-27.

5.6.3 Subnational Studies

As opposed to national-level studies, where the full environmental impact is allocated to either a domestic or foreign consumer, a range of applications occurs at the subnational level. For example, assessing the requirements of a city on its hinterland was directly in line with the

Table 5.3 Comparison of MRIO and EEBT approaches (Peters, 2008)

Criteria	MRIO	EEBT
System boundary	Global emissions from final consumption	Domestic emissions from total consumption
Trade data	Bilateral trade split between intermediate and final consumption	Bilateral trade data (total consumption)
Allocation of intermediate imports	To final consumption	To producing region
Comparable to LCA	Yes	No
Comparable to bilateral trade data	No	Yes
Complexity	High	Low
Transparency	Low	High
Applications	Product or consumption specific	National emissions inventories
Global production analysis	In-depth studies	Limited to bilateral trade flows

original concept of the ecological footprint. A large number of studies have been undertaken at the city or regional level, and footprint-type measures have been integrated into environmental reporting of such entities. Clearly, the environmental burden of residents stretches beyond a city's limits. Agriculture and resources almost always come from outside of a city. However, the footprint can still give some insight into the self-sufficiency of a region, whilst also allowing comparisons to be made at the per capita level in order to understand the impact of planning decisions on global issues. Boundary issues do arise, however, as cities serve both residents as final consumers of goods and services, and businesses and industries, which provide goods and services as intermediates to other regions.

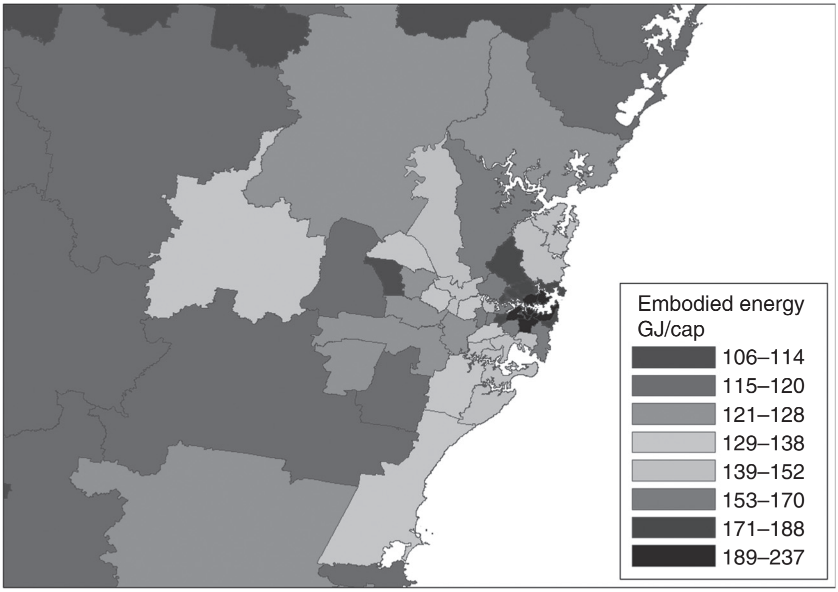
A whole field of regional input–output analysis exists, aimed at accurately determining a regional level of detail for Q^r, below the national level (Hewings and Jensen, 1989). However, often, for simplification, an input–output database equivalent to the national table is taken, just that the final demand is no longer the national-level demand, but a component of the demand, specified here as y^{r*}: the contents of the demand range from cities to businesses, households and products. From equation (5.14), we know the multipliers (embodied impact per unit demand) for a certain region: the impact in a subnational study then assumes that the impact D^{r*}

Table 5.4 *Greenhouse gases embodied in exports of EU-27, top 15 product groups, MRIO approach vs EEBT approach*

	EU-27 Exports – MRIO Approach			EU-27 Exports – EEBT Approach		
#	Product	Gg	%	Product	Gg	%
1	Chemicals and products	92.6	10	Water transportation	71.1	12
2	Machinery and equipment	81.5	9	Machinery and equipment	52.5	9
3	Water transportation	81.2	9	Chemicals and products	48.7	8
4	Motor vehicles	72.6	8	Motor vehicles	41.5	7
5	Air transport services	37.6	4	Air transport services	32.2	6
6	Basic iron and steel	29.2	3	Basic iron and steel	14.5	3
7	Electrical machinery	23.9	3	Electricity by coal	13.3	2
8	Communication equipment	22.7	3	Fuel oils	11.9	2
9	Other transport equipment	22.5	3	Electrical machinery	11.7	2
10	Fabricated metal products	19.8	2	Dairy products	11.7	2
11	Furniture	15.6	2	Fabricated metal products	11.3	2
12	Dairy products	14.8	2	Other transport equipment	11.3	2
13	Fuel oils	14.6	2	Hotels and restaurants	10.0	2
14	Hotels and restaurants	14.6	2	Pulp, and paper products	9.1	2
15	Pulp, and paper products	14.5	2	Bricks and tiles	8.9	2

Table 5.5 *Greenhouse gases embodied in imports of EU-27, top 15 product groups, MRIO approach vs EEBT approach*

	EU-27 Imports – MRIO Approach			EU27 Imports – EEBT Approach		
#	Product	Gg	%	Product	Gg	%
1	Crude petroleum	80.0	6	Crude petroleum	73.9	7
2	Chemicals and products	67.7	5	Chemicals and products	56.2	5
3	Communication equipment	43.8	3	Air transport services	37.3	4
4	Machinery and equipment	43.5	3	Hotels and restaurants	34.9	3
5	Air transport services	40.0	3	Iron ores	34.2	3
6	Hotels and restaurants	39.2	3	Water transportation	33.2	3
7	Water transportation	38.3	3	Machinery and equipment	32.6	3
8	Motor vehicles	38.2	3	Furniture	30.5	3
9	Furniture	35.6	3	Wholesale trade	29.6	3
10	Iron ores	35.5	3	Motor vehicles	28.7	3
11	Wholesale trade	33.9	3	Land transportation	25.0	2
12	Textiles	30.1	2	Rubber and plastic products	24.2	2
13	Clothes	30.0	2	Communication equipment	24.2	2
14	Land transportation	29.1	2	Textiles	24.1	2
15	Transport equipment	29.0	2	Gas oils	23.8	2



Source: Lenzen et al. (2008).

Figure 5.7 Embodied energy for the greater metropolitan area of Sydney

of the demand y^{r*} is informed by the average production process in that region Q^r: $D^{r*} = Q^r\, y^{r*}$.

Some stand-out studies include Larsen and Hertwich (2010) who provide an assessment for 429 municipalities of Norway, finding, at least for Norway, an optimal size of municipalities with regard to population versus carbon footprint. They further argue about the importance of indirect emissions when planning. Lenzen et al. (2008) show results for the City of Sydney and surrounds (Figure 5.7) – with inner city suburbs with high wealth having in the order of double the embodied energy impact compared to outer suburbs.

5.6.4 Business

Some efforts across businesses have been implemented in order to capture embodied impacts of business operation (Wiedmann, Lenzen and Barrett, 2009). Huang et al. (2009) survey the benefits of applying input–output to corporations – specifically looking at the issue of scope 1, scope 2 and scope 3 emissions. One key result they conclude is that trying to specify generic cut-off criteria can lead to misplaced efforts across different sectors.

Larsen et al. (2013) show an application for a university, finding high emissions embodied in the equipment purchases as well as through property management. Lenzen and Peters (2010) use the input–output framework in a more prospective way, looking at both demand-pull and supply-push impacts of changes in demand/supply as a way to help plan resource allocation in a university. Further earlier studies using input–output on institutions include Wood and Lenzen (2003) and Baboulet and Lenzen (2010).

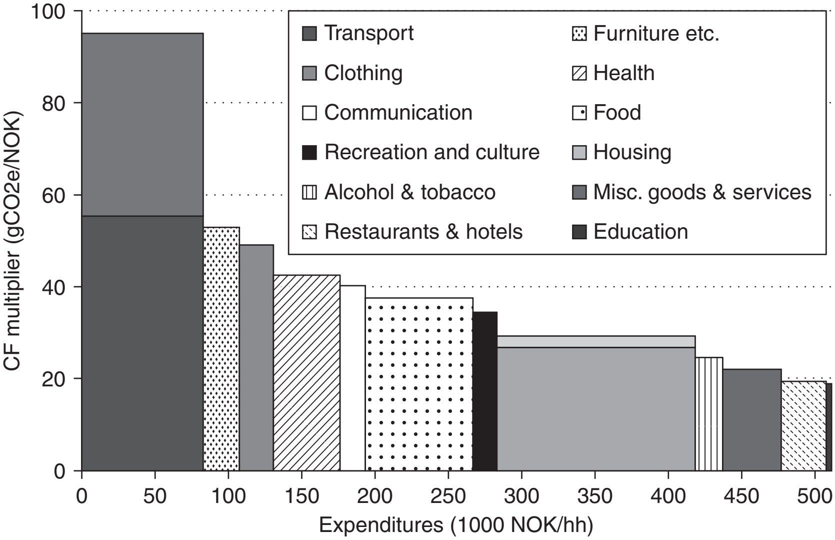
5.6.5 Households

Applications of environmental input–output analysis to household expenditures has been one of the most fruitful areas over the last decades, with detailed expenditure data linked to socioeconomic characteristics to determine the main drivers of environmental impact. Robert Herendeen was instrumental in connecting expenditure surveys to input–output analysis to analyze energy use in the 1970s (Herendeen and Tanaka 1976; Herendeen 1978), which became particularly relevant in the years of the oil crisis. Steen-Olsen, Wood and Hertwich (2015) present the impacts according to consumption category of households in an updated work for Norway (Figure 5.8). The area covered shows the total impact in terms of greenhouse gas emissions, showing the importance of highly manufactured goods and services in complement to traditional areas such as transport and housing, which have large direct impacts.

Lenzen, Wood and Foran (2008) plot energy requirements by expenditure amounts in Figure 5.9 – showing the clear difference in impact of expenditure of direct vs embodied amounts – as people get wealthier, their direct use of energy does not rise, but their energy footprint (the inclusion of embodied energy) goes up significantly.

Breaking these relationships down into consumption categories as per Figure 5.8, we see almost unitary expenditure elasticities for most consumption categories – generally, a unit increase in expenditure drives between 0.8 and 1 unit increase in greenhouse gas emissions (Figure 5.10). The exception is food, which shows a much lower elasticity.

Convincing consumers to reduce incomes and expenditures is often a difficult proposition, so many authors have tried to uncover the drivers of this increase in environmental footprint, using regression analysis to analyze the impact of different socioeconomic explanatory variables. An example across multiple countries is Lenzen et al. (2006), who find that the income effect varied when looking at different countries, and that socioeconomic variables had a more consistent (even if of differing importance)



Note: COICOP = Classification of Individual Consumption According to Purpose.

Source: Steen-Olsen (2015).

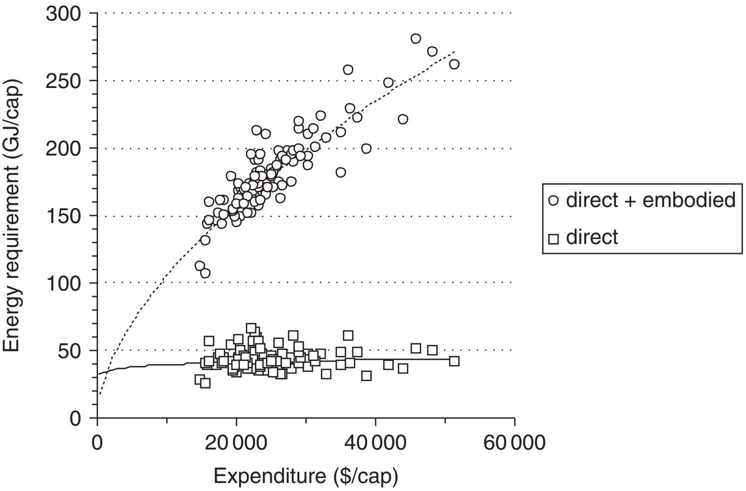
Figure 5.8 Norwegian household expenditures and the average carbon footprint intensities of each COICOP division, 2012. The lighter shaded parts of the "Transport" and "Housing" columns constitute direct emissions by households

impact (Table 5.6). Much work is ongoing in analyzing these outputs of input–output-based footprint results.

5.6.6 Product Level

In going beneath the household level, for individual attempts to mitigate impact on the environment, a first step for many is understanding the environmental impacts of their consumption, based on the goods and services consumed. Citizens feel empowered by driving change through their choice of what they consume. If a citizen wants to reduce their personal footprint, whilst also sending a message to producers, one of the easiest ways is through what is known in the corporate sense as "green procurement." Products are selected not only considering their functionality and cost, but also their environmental impacts.

An example of a significant study at the product level done for the European Commission was through the EIPRO or Environmental



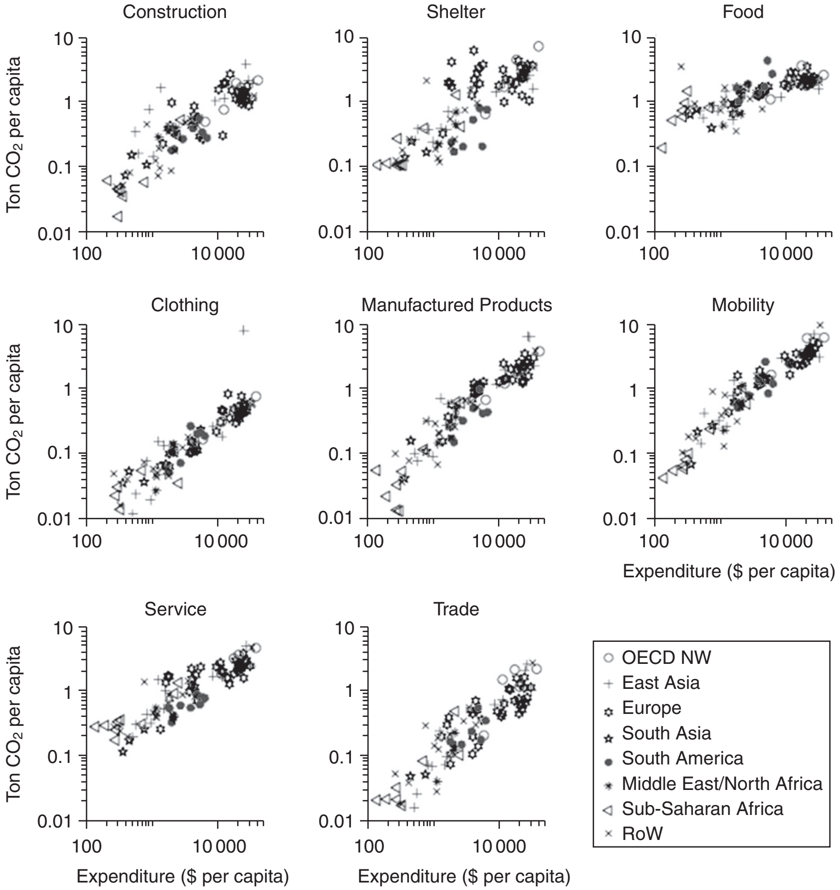
Source: Lenzen, Wood and Foran (2008).

Figure 5.9 Direct and embodied energy of Australian households

Impacts of Products study (Tukker et al., 2006). The study performed both a bottom-up (life-cycle analysis) and top-down (input–output analysis) of European consumption as part of an integrated product policy that sought to use a market-driven approach that incorporated aspects of both competitiveness and social concerns. The objective of the study was to identify which products had the "greatest environmental impact, throughout their life-cycle, from cradle to grave, as measured separately by different categories of environmental impact, in physical terms" (Tukker et al., 2006).

As product policy requires a higher delineation of aggregate product groups that are evident in many input–output tables, the EIPRO study used a hybrid of the detailed United States table to provide detail below an estimated European Union table. Breaking the economy down into some 400 product groups, results were also aggregated over a range of environmental impacts using subjective weighting, as shown in Figure 5.11.

A second example from a more recent multiregional input–output database shows the consumption categories aggregated over the product groups (Figure 5.12). The purpose of such work is to show the importance of diffuse product groups such as services in the overall footprints of a population. Whilst services clearly embody the lowest multiplier (impact per euro spent), their importance in developed nations is becoming such that the total contribution of the sector through their embodied impacts is non-negligible.



Source: Hertwich and Peters (2009).

Figure 5.10 Per capita CO_2 emissions versus expenditure for different consumption categories

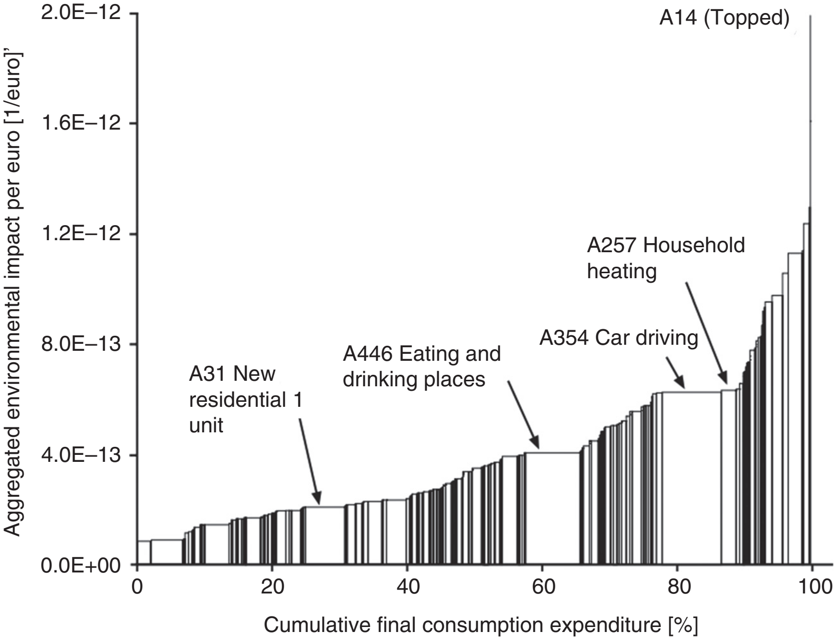
5.6.7 The Link to Policy

The importance of trade in assessing the carbon footprint of a population has been a strong focus of research over the last decade or so (Peters and Hertwich, 2006; Wiedmann and Minx, 2007; Hertwich and Peters, 2009; Wiedmann et al., 2010). The attention drew from the need to accurately include production technologies in trade partners that were radically different to local technologies (Peters and Hertwich, 2006), at least in terms

Table 5.6 *Effect of explanatory variables on household carbon footprint*

	Australia			Brazil			Denmark		
Rank		m Δm	|t|		m Δm	|*t*|		*m* Δm	|*t*|
1	Expenditure	0.78 ± 0.02	45.6	Expenditure	1.00 ± 0.01	79.5	Expenditure	0.86 ± 0.02	35.8
2	Size	−0.02 ± 0.01	3.6	Education	1.62 ± 0.05	30.3	Size	−0.22 ± 0.02	13.7
3	Age	0.13 ± 0.03	3.9	House type	3.68 ± 0.17	21.1	House type	0.16 ± 0.02	7.1
4	Education	−0.04 ± 0.01	3.1	Urbanity	−0.08 ± 0.01	7.7	Urbanity	−0.11 ± 0.02	4.6
5	Urbanity	−0.01 ± 0.00	2.9	Size	−0.07 ± 0.02	4.5	Age	0.13 ± 0.03	4.2
6	House type	0.04 ± 0.02	2.5	Age	0.55 ± 0.17	3.2	Employment	0.02 ± 0.02	1.0
7	Employment	0.06 ± 0.08	0.8	Employment	−0.10 ± 0.04	2.6	Education	0.01 ± 0.02	0.6
	India			Japan					
		m Δm	|*t*|		m Δm	|*t*|			
1	Expenditure	0.86 ± 0.002	362.5	Expenditure	0.64 ± 0.08	8.5			
2	Urbanity	0.07 ± 0.003	23.6	Urbanity	−0.04 ± 0.01	7.7			
3	House type	0.03 ± 0.001	23.5	Size	0.06 ± 0.03	1.7			
4	Age	0.08 ± 0.004	22.8	Employment	0.15 ± 0.10	1.5			
5	Education	0.02 ± 0.001	18.9	House type	0.05 ± 0.04	1.2			
6	Size	−0.01 ± 0.001	17.1	Age	0.15 ± 0.28	0.5			
7	Employment	0.00 ± 0.002	1.5	Education	-6.39 ± 9.02	0.7			

Source: Lenzen et al. (2006).

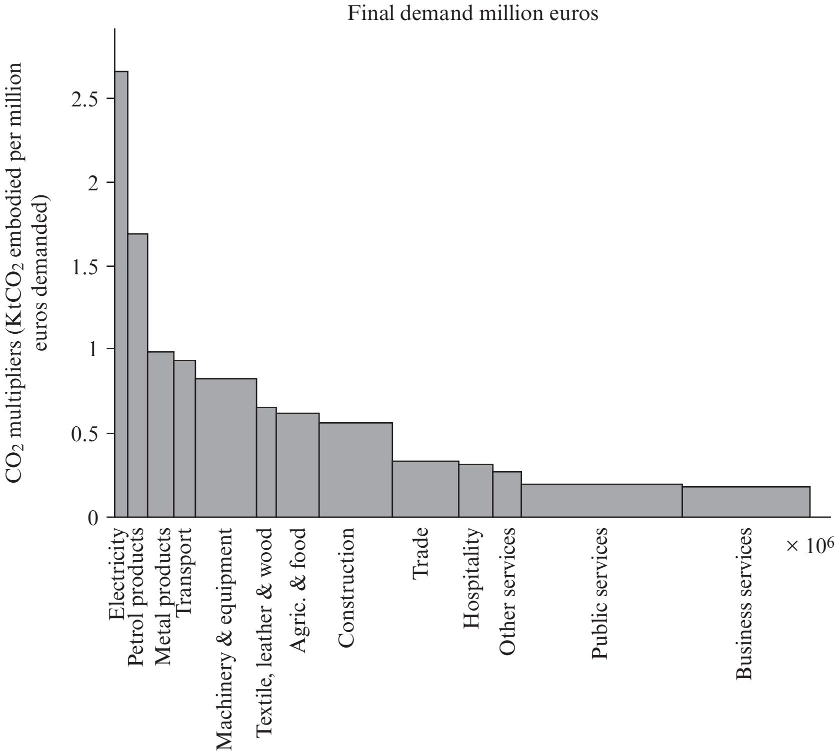


Source: Tukker et al. (2006).

Figure 5.11 Environmental impacts of final consumption, in ascending order of impact per euro

of emitted greenhouse gases. Such analysis allows for the calculation of emissions embodied in imports, exports, and those attributed to the domestic consumer. This provides an alternate perspective to the responsibility of emissions and emissions reduction. Such "carbon footprints of nations" (Hertwich and Peters, 2009; Davis and Caldeira, 2010) allows a differentiated approach to addressing action on carbon emissions – not only is it the producing nation who should attempt to reduce the level of their emissions, but also consuming nations that are driving emissions through increased demand and having certain trade relationships that must take some of the burden. A huge quantity of research has been done (which we will not review here) on the use of input–output analysis in calculating emissions embodied in trade and consumption over the last ten years.

In policy circles, addressing greenhouse gas emissions from a consumption-based carbon approach is becoming seen as an alternative way to address the growth in greenhouse gas emissions. Targets under the Kyoto



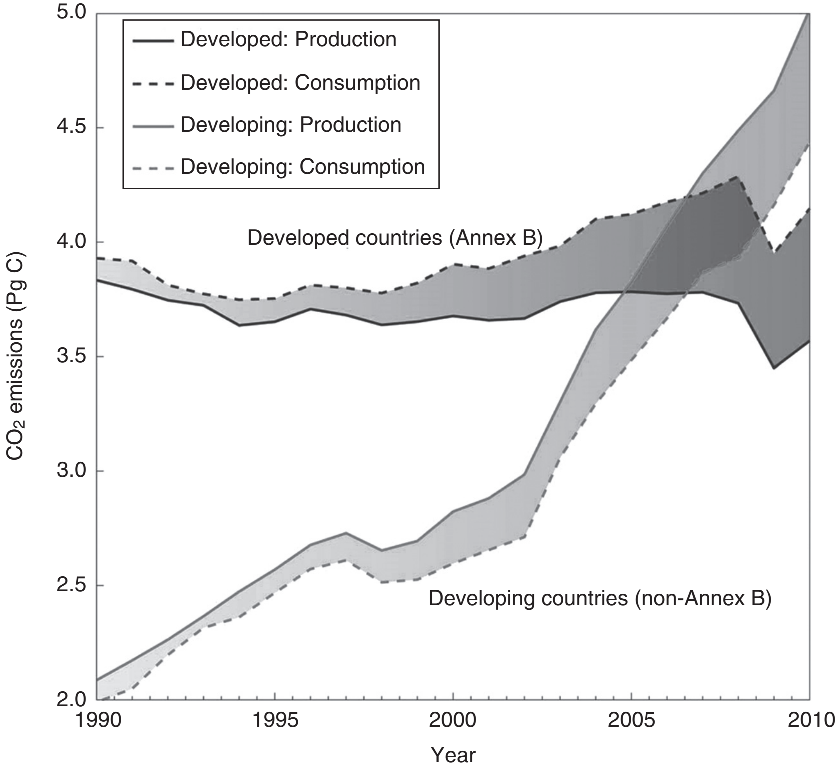
Source: Own calculations based on Wood et al. (2015).

Figure 5.12 Product-level results showing embodied greenhouse gases in final products consumed for the EU in 13 product groups

Protocol could be set from a consumption-based approach as opposed to the standard territorial approach. This would encourage developed countries to consider the impacts of their population rather than just their production. Consumption-based approaches can further encourage cooperation between producers and consumers in reducing greenhouse gas emissions, and potentially help improve the design of climate mitigation policies.

The results are stark when viewed from developing versus developed countries over time (Peters et al., 2012). Large increases in emissions continue, and the overall carbon footprint of developed countries has only reduced during periods of recession (Figure 5.13; Peters et al., 2012).

Since 1990, the increase in emissions embodied in trade (net import)

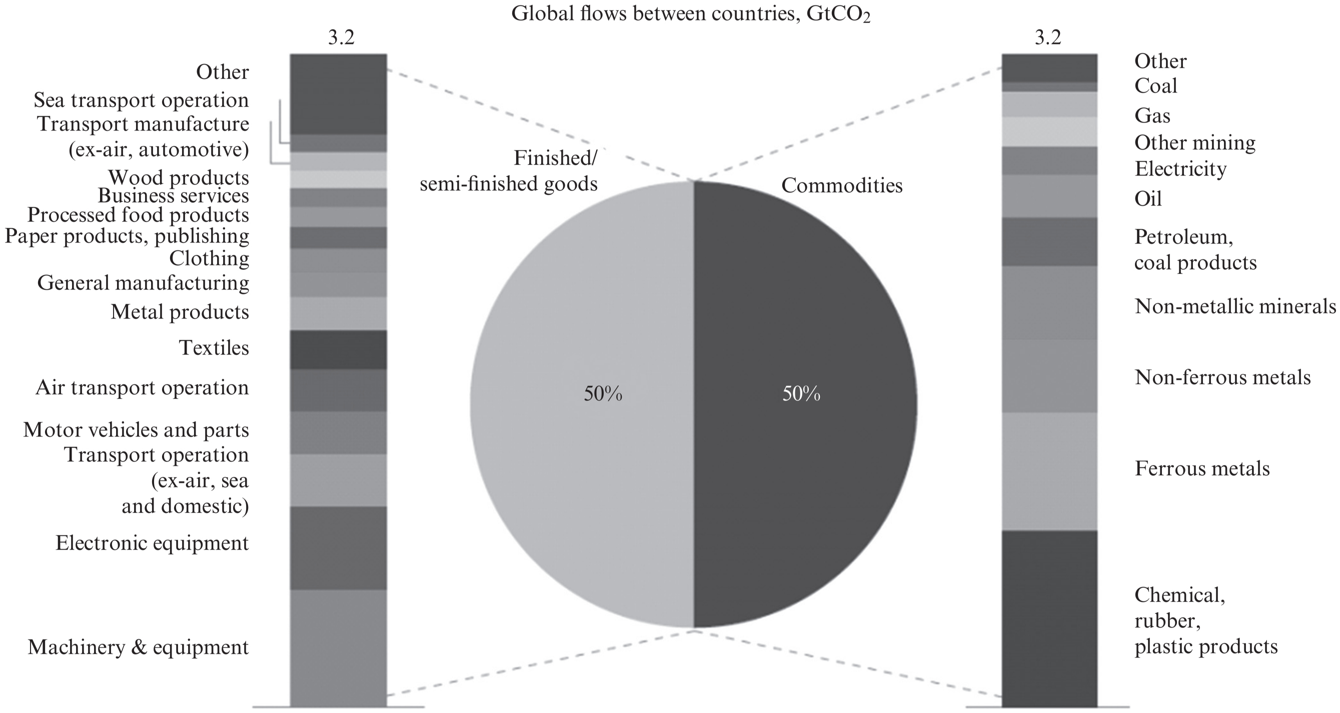


Source: Peters et al. (2012).

Figure 5.13 Production versus consumption approaches – developments of greenhouse gas emissions over time

has increased five times the overall emissions reduction achieved in Annex B countries. Half of these emissions are embodied in energy-intensive commodities, but half are embodied in finished or semi-finished products (Figure 5.14).

Hence the question has been raised is whether carbon leakage (shift of production to other regions) due to climate policies is really a risk given the fact that we have already seen large off-shoring of energy-intensive commodities without active climate policies. Peters et al. (2011) look at this issue, dividing analysis into strong carbon leakage and weak carbon leakage. Strong carbon leakage is defined as the amount of production relocation directly due to a climate policy, whereas weak carbon leakage is production relocation irrespective of any climate policies. Peters et al.



Source: Carbon Trust (2011).

Figure 5.14 *Division of CO_2 embodied in products in global trade, 2004*

(2011) conclude that strong carbon leakage has had minimal impact on trade, whereas it is likely that the major shift that we have observed are due to factors currently unrelated to climate policy.

We are hence faced with the question of whether input–output-based research can help drive policy to tackle this type of carbon leakage that we are already experiencing. Policy directives that tackle the growth in emissions have been derived from a demand or lifestyle perspective. Environmental footprint approaches have shown the importance of consumers and the role that they play, but we have seen limited impact in reducing impacts by changing the types of products we consume or by implementing technological change.

5.7 CONCLUSIONS AND OUTLOOK

Use of input–output analysis for studying the environmental impacts of our societies has a long history, and probably, a rich future. As data quality and availability improves, as our systems of production become more and more complex, we are likely to see ever more of a need to provide the tractability of our supply chains underpinning our global socioeconomic organization. As our societies develop, as our economies progress to a service-based economy, we must still be aware of the link back to our basic resource requirements. By systematically including economy-wide (and we should also mention that much can also be done on "environment-wide") approaches to our trade and consumption habits, we can be sure that the sustainable livelihoods that we seek to attain are not just hiding the problem under the cloak of globalization.

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