LUNDS UNIVERSITET

Embodied Ecological Footprints in International Trade

LUMES Master's Thesis

Daniel Moran[1]

Supervisor: Barry Ness[2]

[1] 14701 Farwell Ave. Saratoga, CA 95070 USA
[2] LUCSUS, Lund University, Sölvegatan 10 4° van, Lund 222-44 SWEDEN

Abstract

Nations import and export biophysical resources. With many ecosystems worldwide under mounting stress, countries may be increasingly interested in knowing the extent and origin of their ecological imports and dependencies. In this paper the Ecological Footprint is used as a tool to measure the biophysical (as opposed to financial) value of international trade flows. This paper attempts to answer the following question: How large of an Ecological Footprint does a given country exert inside the borders of each of its trading partners? Records in the UN COMTRADE bilateral trade database are multiplied by a matrix of per-product footprint yield coefficients to translate from values in dollars and tonnes to units of hectares. This primary intent of this paper is to introduce a methodology, but some first-order analysis of the findings is presented, including findings on the global North/South ecological trade balance. Two data visualization approaches, one based on flow mapping and one on spatial analysis, are offered as techniques to aide in further analysis of the results.

Acknowledgements

Mathis Wackernagel has been a mentor, teacher, friend, and at times, a second father to me; if I have accomplished anything in this project it is to him I owe the most. I have been blessed to have a wonderfully supportive and loving travelling companion in my life through my studies and this work. For everything: СПАСИБО, СПУТНИК. From LUCSUS my supervisor Barry Ness has generously offered warm guidance through the writing of this thesis. Turaj Faran at LUMES has been one of the best teachers I have ever had the benefit of knowing: with deep respect he sees the maximum capacity of each of his students and strives to never let them expect any less of themselves. At Global Footprint Network, Justin Kitzes, Audrey Peller, Steven Goldfinger, and Michael Murray have contributed at some stage to almost every aspect of this paper. Benjamin Heumann and Doantam Phan each applied their genius for software and visualization to contribute crucially to the maps presented here.

Table Of Contents

1. Introduction

1.1. Background

One of the transitions prescribed by the sustainable development agenda is toward dematerialization of human economies. In order to reconcile the goals of human development with the environmental capacities of the planet, the sustainable development agenda calls on nations to develop more materially efficient knowledge and service-based economies which can provide increasing human welfare while holding steady or decreasing the amount of physical material metabolized to provide that welfare (Ehrlich and Holdren 1971). The remarkable progress of development since WWII has come at a high cost to the biosphere. Numerous reports document the fact that ecosystems worldwide are under mounting stress (MEA 2005, Thomas*, et al.* 1956, Turner*, et al.* 1990, Vitousek*, et al.* 1997). De-coupling economic growth from underlying biophysical flows is a goal of sustainable development for two reasons. First, de-coupling can help avoid the risk that ecological degradation will generate economic problems. And second, de-coupling creates the opportunity for societies to continue to progress without ecological constraints.

A first step toward de-coupling is to develop metrics for quantifying the biophysical flows underlying the economy. The project of natural resource accounting (a specialization within the emerging field of sustainability science) works to develop tools that measure the ecological, as opposed to the financial, balance of trade. As globalization accelerates, many nations depend on natural resources and ecological services from abroad. And as the global economy becomes more highly articulated and specializations deepen, many trade relationships will grow more asymmetrical in ecological terms while they remain close to parity in financial terms. While increased specialization and trade maximizes worldwide productivity of natural resources, the leverage comes at the price of increased interdependence, which magnifies the stakes in the event of local ecological destabilizations.

This paper describes a tool to quantify each nation's imports and exports of natural resources and ecosystem services with their trading partners. Specifically, this paper attempts to answer the question: How large of an Ecological Footprint does a given country exert inside the borders of each of its trading partners?[1] International trade can be quantified in terms of its Ecological Footprint, or the land area required to provide various products and services. Land used to produce export products is considered a

[1] Nations also exert ecological impacts on not only on the territory of other nations, but also on the global commons. This is the case with deep sea fishing and atmospheric pollution. The methodology developed distinguishes Footprint impacts exerted on the global commons and on individual nations.

Footprint export, and land used abroad to provide imported goods and services is considered a Footprint import. Using the results generated by the method described in this paper, several hypotheses regarding the ecological balance of trade are tested.

1.2. Paper summary

Following this overview, Section 2 surveys the debate over the implications of ecologically asymmetrical trade in order to explain why nonmonetary measures of trade are useful. Several critiques of the neoclassical conclusion that markets will optimally allocate ecological resources are summarized. I suggest that 'biosecurity' – the idea that some natural resources are essential to national security and should be more closely accounted for in a the present era of growing ecological instability – and a land stewardship ethic may be two powerful frames in which to discuss ecologically unequal exchange.

Section 3.1 evaluates various metrics which may be used to measure ecologically unequal exchange. The Ecological Footprint (EF) metric (Wackernagel and Rees 1996) is found to be especially suitable. The EF is a particularly applicable tool for this task since it has a clear research question and clear system boundaries – two strengths which make it better suited for macro analysis than similar tool such as LCA (Life-cycle analysis) or energy-based analyses. Monetary measurers of sustainable trade (e.g. the Genuine Progress Indicator described by (Daly 1996), and similar (Lawn 2003)) are not evaluated as the intent of this study is to focus on non-monetary measures of trade flows.

Section 3.2 describes a method for calculating the embodied Ecological Footprint in trade flows. The UN COMTRADE international trade database (UNSD 2007) is multiplied by a matrix of per-product Footprint yield coefficients (t/ha). This matrix, which we refer to as a Product Land Use Matrix or PLUM, is derived from Global Footprint Network's National Footprint and Biocapacity Accounts (GFN 2006). The result is the complete COMTRADE bilateral trade database translated into units of Footprint hectares. In addition to discussing the tool and methodology, Section 3.2 also contains a discussion of the limitations and potential refinements of the method.

Section 4 presents the results both numerically and using two approaches to data visualization. The data visualizations (based on Heumann 2006, Phan, *et al.* 2005), illuminate where countries exert an Ecological Footprint beyond their borders. Results are discussed, several common hypotheses regarding the ecological balance of trade are tested, and the results are compared to similar studies. Section 5 concludes.

1.3. Methodological basis

This study represents the first global, bi-lateral assessment of international trade using the Ecological Footprint. Weidmann *et al.* (2007) and Turner and *et al.* (In press) have described a method to calculate a multi-region, bilateral, inter-sectoral analysis of embodied Ecological Footprint in trade using the input-output (I-O) methodology originally developed by Leontief (1970). However limits of data availability and computability have so far held back implementation of these methods. The MOSUS project (Lutz, *et al.* 2005) is working to assemble the necessary input-output data tables and Weidmann estimates a global I-O based trade analysis will be implemented within three years.[2]

The I-O approach has the essential advantage of being able to track the transformation of goods through an economy, tracing impact from final product back to raw resources. I-O tables also capture the impact of exchanged services. In contrast, the coefficient approach used here can only see a single step in the supply chain, a product's most recent source. The disadvantages of I-O are poor data availability and low product resolution. Few non-OECD nations publish trade statistics in I-O table format and most I-O tables typically disaggregate 20 industrial sectors, as compared to the >1000 products distinguished in COMTRADE. The method developed in this paper does not follow the traditional I-O formulation but Weidmann *et al.* (2007) have mathematically demonstrated this approach is a special case of a generalized input-output calculation. It is likely that future work in this area will move toward a hybrid mode combining the strengths of I-O method and the coefficient approach used here.

At a regional scale a number of authors have studied individual countries to calculate their Ecological Footprint in each of their trading partners. Andersson and Nevalainen (2003) conducted such a study for Finland (See section 4.2.1 for a comparison of results). Hornborg (2005) uses the same approach used in this study to analyse the historical terms of trade in Footprint units of key agricultural commodities traded between the US and Britain during the 19th century. Hornborg estimated historical yields for cotton, wheat, and wool and applied them to historical trade records not with the intent of evaluating Britain's total foreign Footprint but in order to compare the mix of land, labour, and capital embodied in exports as compared to imports. A number of other studies propose or conduct I-O based analyses for countries and regions (Bagliani, *et al.* 2003, Bicknell, *et al.* 1998, Ferguson, *et al.* 2004, Hubacek and Giljum 2003, Lenzen and Murray 2001, Munksgaard, *et al.* 2005) and product lifecycles (Joshi 2000). Peters and Hertwitch (2006) extended an I-O based study of Norwegian trade using structural path analysis to reveal the most common trade paths taken through Norway. Tukker (2006) *et al.* are currently running an EU project using I-O methods to study intra-EU trade using, among other environmental indicators, the Ecological Footprint.

Other studies have assessed international trade using other biophysical metrics. A large body of research uses material flow analysis to trace specific harmful or valuable

---

[2] Wiedmann (2007), personal communication.

substances through economies and supply chains (c.f. Graedel and Allenby 1995). Matthews *et al.* (2000) have calculated the material balance of trade for the industrialized nations. Nijdam *et al.* (2005) use I-O trade data and a set of environmental load indicators to assess the Dutch environmental load abroad.

Assessing the embodied CO_2 emissions in trade has been an active topic of research. The hypothesis being tested is: pollution and CO_2 intensive manufacturing moves from developed to less developed nations. The degree to which this actually occurs has been heavily debated in the literature. Grimes and Kentor (2003) survey the literature. Notable papers on the topic include (Ahmad and Wyckoff 2003, Bastianoni, *et al.* 2004, Ferng 2003, Lenzen, *et al.* 2004, Mongelli, *et al.* 2006, Munksgaard, *et al.* 2007, Munksgaard and Pedersen 2000). The results of Ahmad and Wyckoff are widely cited; see section 4.2.4 for a comparison of our and their findings. Their study did not disaggregate to individual trading partners. Chung (2005), working with the GTAP trade database (Dimaranan and McDougall 2002), has calculated bilateral embodied CO_2 flows for countries and regions centred around Southeast Asia.

2. Ecologically unequal exchange: Why mind?

2.1. Arguments for biophysical accounting

Ecologically unequal exchange occurs when trading partners have a mutually satisfactory balance of trade in financial terms but the ecological balance of trade is asymmetrical. That trade is often unequal in physical terms is hardly a new observation. Why look at trade then? So long as it is voluntary and participants have full information, free exchange will always be normal and equitable. Both parties benefit, and, according to the neoclassical economic paradigm,[3] nations will specialize in their ecological comparative advantage and collectively generate the greatest possible benefit for society as a whole.

Against the neoclassical conclusion that well-functioning markets will optimally allocate scarce ecological resources I identify five lines of critique, all of which justify biophysical accounting: (1) Environmental economics and ecological economics argue that, for a variety of reasons, ecological assets tend to be under-priced and thus not efficiently allocated by free markets. Biophysical accounting can help markets get prices right. (2) Certain ecological assets may be essential to the integrity of nations. As population grows and ecological capital deteriorates, national interest in 'biosecurity' may fuel interest in natural resource accounting. (3) Natural resources are unevenly

[3] For an effective interpretation of the neoclassical economic paradigm applied to ecological goods, see Lomborg (2001).

distributed across the planet. Some resources, such as clean water, that should be shared by all will not necessary be equitably allocated by a free market. Critiques (4) and (5) come from the radical voices of deep ecology and neo-Marxism, which argue that any trade in goods with ecological impact deteriorates irreplaceable natural capital and engenders geopolitical instability by concentrating control of natural capital. We consider each argument more closely.

2.1.1. Arguments against the Efficient Market hypothesis

This line of critique argues that ecological assets tend to be systematically undervalued for a variety of reasons. The field of ecological economics has worked extensively to demonstrate this and expose the mechanisms by which this mis-pricing occurs. The reader is referred to (Daly and Townsend 1993, Norgaard 1990, Rees and Wackernagel 1999) for summaries of the literature. Most of these arguments exist within the 'strong' sustainability paradigm (Ayres, et al. 2001). If one follows 'strong' sustainability and rejects the notion that manmade capital can substitute for natural capital, then it is dubious to use a single metric (money) to value both.[4] But even under the weak sustainability paradigm, in which manmade capital can fully substitute for natural capital, prices are not unproblematic. For prices to accurately reflect the ecological value of goods the market must not be experiencing any failures such as externalities (caused by incomplete or weak property rights), imperfect information, or imperfect competition. Such ideal market conditions are not found in the real world. As evidence that prices are an in practice an unreliable indicator of physical scarcity, Farrow (1995) found that neither the sudden collapse of the North American buffalo or passenger pigeon was anticipated in consumer prices of related goods. Uncertain information about the future value of natural resources also impacts prices.

Price signals are so-called because they are essentially a system of information exchange. But they reflect more than mere information. A good's price reflects how much people want it, how much they *value* it. Goods consumers want become subject to intensive competition and the price drops. Assessments of ecological value have two faces: in one light they supply missing information and may help consumers calculate the utility they perceive from a good, and in another they tacitly raise awareness of the biosphere in which we live and nudge consumers to place a higher value on the planet. Any attempt to "inform" or "correct" prices must admit to having some normative motive implicit, if not express.

---

[4] This problematique underlies the extensive debate in the literature over the proper discount rate to apply to natural capital. Goods which have no substitute, such as oxygen generated by green plants, should, in the strong sustainability paradigm, have a high or infinite discount rate in order to ensure they are not diminished. For a survey of the issue on the discount rate of natural capital see Howarth and Norgaard (1992)

Adherents of strong and weak sustainability can both agree that traditional financial accounting of natural resources (and the trade thereof) does not necessarily accurately reflect the value of those resources. How then to prevent the occurrence of mis-pricing? Extra-financial accounting can reveal situations where information is not properly priced in. As observed in the capital markets, investors regularly seek information not known by others in order to gain profit. The field of biophysical accounting attempts to introduce information not currently factored into resource prices.

Non-monetary metrics are valid and important for optimal allocation of ecological goods. This conclusion justifies the study of biophysical accounting. But it falls well short of being motivational. I propose two frames which may make the study of ecologically unequal exchange more relevant to policymaking.

2.1.2. Biosecurity arguments

Nations understand the importance of knowing their financial balance of trade, and they closely monitor it. Not monitoring them would be considered shortsighted. The same logic should apply to ecological assets, but it is often not. Nations should be concerned if ecological conditions deteriorate in areas upon which they rely for resources. Today, countries face increasing ecological risks and but are mostly blind to them.The persistent threat of resource wars, and the growing trepidation over the financial (e.g. Swiss Re 2002) and military (Schwartz and Randall 2003) implications of climate change suggest that ecological instability is already entering the stage as a national security issue. We may term this idea ‘biosecurity’. Numerous reports, such as the Global Environmental Outlook reports from UNEP (2002), the World Resources database from the World Resource Institute, The State of the World and Vital Statistics from Worldwatch (2007), the Living Planet Report series from WWF International (2006), IPCC reports on climate change (2001), IGBPs Global Change and Earth System (Steffen, *et al.* 2005), and the Millennium Ecosystem Assessment (2005), have demonstrated the endangered health of ecosystems worldwide. The non-monetary balance of trade and strategic reserves of steel, petroleum, weapons technology, or trained engineers, has always been considered with central importance by states. That ecological assets should be added to the list of resources essential to sovereignty has been a longstanding argument of the bioregionalist school (McGinnis 1999). From a world-system theory perspective, Bunker and Ciccantell (1999) argue that the trade in and securing of natural resources is a powerful explanatory variable in the history of development. Biophysical accounting is uniquely able to help nations understand their ecological dependencies.

2.1.3. Equity arguments

The other tack to politicizing ecologically unequal exchange rests on questioning its ‘fairness’. There are several typical arguments for why ecologically unequal exchange is unfair:

1. Prices undervalue natural resources. This is disproportionately harmful to poorer nations as they are typically more dependent on biophysical exports, and are undercompensated for their exports. (Andersson and Lindroth 2001)
2. Some ecological assets (e.g. water, clean air) should be rationed equally to all people. Markets are optimal for allocating scarce resources given starting distributions but are not able to ensure fair starting allocations. Biophysical accounting can effectively reveal when resources are distributed unequally. (Weterings and Opschoor 1994)
3. Nations exerting an Ecological Footprint abroad should take some care or interest that the place their footprint falls is well cared for. They should take a stewardship concern for their Footprint wherever it falls if not for ethical motives then to ensure the continued smooth supply of resources.
4. Prices don’t reveal environmental burden shifting. Ethically distasteful international pollution transfers and burden shifting are best revealed by biophysical accounting (as argued by, among many others, Muradian and Martinez-Alier 2001, Schutz*, et al.* 2004).

These two frames of security and social justice can provide strong bases from which to draw policy conclusions. Before moving on we must acknowledge one other angle of critique against ecologically unequal exchange.

2.1.4. Anti-capitalist critiques

Two other theories criticize the capitalist system that gives rise to the occurrence of ecologically unequal exchange. The first is a conservationist, bio-centric mindset, which views almost all but the most limited human economy as either dangerous or outright harmful to the planet and/or that civilization itself (cf. Næss 1989, Shiva 1988). In this worldview the use of ecological goods and services is objectionable *per se*, and any trade in ecological assets will therefore be opposed. Another worldview opposing ecologically imbalanced trade traces its lineage to Marx. Foster (2000) has elucidated Marx’s previously overlooked thoughts on the changing relationship between man and nature, and the Marxist economist Arghiri Emmanuel (1972) is often credited with coining the term ‘unequal exchange’. Extended into development theory, Frank’s theory of underdevelopment (1966) and Wallerstein’s world-system theory (1974) may be classified as neo-Marxist. Essentially, private trade of any sort, including in natural resources, is seen as merely perpetuating the capitalist system which has failed to provide the outcome of social equality it promised. (Hornborg 2001, Martínez-Alier 2003). This argument may have merit on its own. However, using this argument alone to justify the study of ecologically unequal exchange may be to unnecessarily tie that study to the fortunes of a larger liberal ideological agenda.

In summary, this section has argued the following: Natural resources and ecological services can be, and likely are, mis-priced. Non-monetary measures are therefore important to augment and inform price valuations of ecological assets. Being informed of the ecological value of trade and its patterns enables countries to make informed decisions about their ecological interdependencies (e.g. food and energy security) and their desired relationship with the biosphere beyond their borders. As ecosystems around the world come under mounting stresses and risk being destabilized, nations using services from at-risk ecosystems will have both an ethical and a practical incentive to work to ensure a sustainable flow of resources from those areas, be they domestic or abroad.

2.2. Measuring Ecologically Unequal Exchange

Having established the importance of accounting the ecological impact of trade in non-monetary units, what tools can be used to make these measurements? Several have been proposed. These tools measure the ecological weight of trade flows in terms of material, energy, biotic production, or land. Biophysical accounting is not about searching for a perfect unit which can measure the ecological value of natural goods and services. A plurality of metrics is needed (Norgaard 1989, Wackernagel, *et al.* 2002). Using a single unit, be it gigajoules, tonnes, or hectares, suggests just as strongly as using dollars that goods are substitutable within that unit. Here we will survey the leading material and energy-based metrics and I discuss the choice of the Ecological Footprint metric for this study.

2.2.1. Material Flow Analysis (MFA)

Material flow analysis (MFA; also called ‘ecological rucksacks’ when extended to indirect[5] material flows) is one non-monetary measure of the ecological value of trade (Fischer-Kowalski 1998, Haberl, et al. 2004, Schmidt-Bleek 1994, World Resources Institute 1997). Flows are measured in tonnes, and countries are net importers or exporters of raw material. MFA can be used to track selected materials, for example to help a business make a product lifecycle more environmentally friendly. A significant

[5] Indirect material flows include all the flows involved in creating a final product. Using a gold ring as example, the gold moved from the mine to the bearer’s finger is the direct material flow and all the earth moved and fuel used in producing the ring are the indirect flows.

drawback to the MFA approach is that weighting all trade on the basis of tonnage is not informative regarding the varying ecological impact of the traded goods. The impact of different goods can vary considerably when viewed purely on a mass basis (van der Voet, *et al.* 2004). EF accounts are built on MFA but extend the concept by offering additional information regarding the ecological value of biophysical flows. One striking finding of this study is that one commodity group, Mineral Products, accounts for ≈50% of the weight of international trade (See Table 2 on page 21). Mineral products (ores, minerals, and fossil fuels) certainly have ecological impacts in their extraction and use, but the weight of their environmental impact is less than proportional to their physical weight. It seems counterintuitive for mineral products to receive such heavy emphasis in a comprehensive assessment of the ecological value of trade.

2.2.2. Energy metrics: eMergy and eXergy

Energy-based metrics such as 'eMergy' (embodied energy or energy memory) or eXergy (negative entropy) are another proposed approach (Costanza 1980, Odum 1971). Goods are measured in terms of how much energy or eXergy is required to provide them. The energy approaches offer a better understanding of the relative difficulty of maintaining given flows than does MFA, but they do not ultimately speak to the varying ecological value of those flows. For most purposes in evaluating environmental impact, the impact on the biosphere is the question, and this does not necessarily correlate with the amount of energy in a flow. Embodied energy is extremely difficult to calculate in practice and it has received more theoretical discussion than implementations. The EF acknowledges within it the eMergy concept: the EF is in a way a measure of solar income (solar income ultimately creates and funds the ecological services of the biosphere), and anthropogenic energy sources (fossil and nuclear energy) are accounted for as well. Thus the EF embraces and extends eMergy to provide information about both the relative and absolute ecological cost of goods.

2.2.3. Net Primary Productivity

Another compelling metric of human demand on the biosphere is Human Appropriation of Net Primary Productivity (HANPP) (Imhoff, et al. 2004, Vitousek, et al. 1986). This tool measures how much of the annual biomass accumulation is appropriated by humans. Imhoff *et al.* call for analysis of global flows of NPP based goods. The EF is very similar to HANPP but it extends the analysis by including draws on non NPP goods (e.g. minerals) and by including the impacts of waste, which HANPP does not. Additionally, the EF, unlike aggregate measures of global NPP, takes an anthropocentric approach and measures only 'useful' biocapacity usable by humanity. In the EF the bioproductivity of land is weighted according to its potential suitability usefulness to man, not its simple carbon accumulation potential. (Haberl, *et al.* 2004b)

2.2.4. The Ecological Footprint

For this study we chose to use the Ecological Footprint to assess the ecological value of international trade. The EF uses biologically productive land area as the basic unit of measurement. Globally, the EF measures how much of the regenerative capacity of the biosphere is appropriated by human activities. It does so by calculating the amount of biologically productive area required to support a given population at its current level of consumption and technology. A country's Footprint is the total area required to produce the food and fibre that it consumes, absorb the waste it generates, and provide space for its infrastructure. Footprints are measured either in hectares (ha) or in global hectares (*gha*), which are hectares of land with world average biological productivity. (Monfreda*, et al.* 2004, Rees 1992, Wackernagel*, et al.* 2005, Wackernagel and Rees 1996).

The EF provides information about the present and potential products and services of the land, and quantifies land and sea areas required to provide mankind with specific ecological products and services. It measures how much biocapacity is required to maintain a flow. Every biophysical flow, from the total flow of resources through a given country in one year to the flow of wheat exported from China to Japan, has an associated Footprint needed to maintain that flow.

The EF has a more specific research question than the generic term 'footprint' might imply. Not attempting to assess 'environmental impact' more broadly, the EF measures simply the use of biologically productive land areas as a result of human activities. The intensity of land use is not addressed directly by the EF, only the areal extent. Flows of non-renewable goods (i.e. non-biological goods) are included in Footprint analysis only insofar as they put a demand on the regenerative capacity of the planet (such as the land area required to absorb the waste from processing and using them). Substances for which nature has no significant absorptive capacity (e.g., non-biodegradable toxic substances) are excluded from Footprint analysis,[6] as one condition for sustainability is that mankind not emit wastes which degrade the biosphere. Additionally, water withdrawals are not presently addressed in EF analysis. These limitations together suggest that the EF most likely underestimates human impact on the biosphere.

When nations consume goods and services the Footprint of those goods and services may fall outside their borders: they can then be said to be 'importing' biocapacity, or productive land area. Conversely, countries exporting goods and services produced using domestic ecological resources are exporters of Ecological Footprint. (In addition to importing and exporting EF area to and from other nations, countries also use

---

[6] Toxic substances are considered implicitly insofar as they reduce biological productivity over time. Decreasing land yields due to toxification is reflected in EF accounting.

resources of the global commons. The issue of how to differentiate between Footprints exerted on other countries and on the global commons is discussed below in the methodology chapter.) Papers from van den Bergh and Verbruggen (1999) and Ayres (2000) have suggested that the EF has an anti-trade bias, arguing that Footprint accounting implies that no country should have an ecological deficit and that trade is therefore ecologically unfriendly. This interpretation is subjective, as the EF methodology has no normative bias, express or implied, penalizing trade.

The Ecological Footprint is enjoying success as both a conceptual model and as a policy tool. The EF is one of the more widely cited environmental indicators used to measure the overall health of the biosphere. According to Dauvergne (2005:17), the EF is 'one of the most innovative ways scholars have tried to compare the ecological impacts of individuals across the globe.' A large body of literature exists examining the strengths and shortcomings of the Ecological Footprint approach (Chambers 2001, Costanza 2000, George and Dias 2005, Neumayer 2004, Schaefer*, et al.* 2006, van den Bergh and Verbruggen 1999). The EF is a popular tool for communicating disparate environmental impacts into one easily understood unit and communicating resource use issues to broader audiences.

Governments and policymakers are increasingly using the EF to plan and evaluate sustainable development agendas (European Environment Agency 2005, Wackernagel*, et al.* 2004, WWF European Policy Office 2005). This demand has fuelled much methodological development aimed at strengthening the EF as a policy tool. Consensus around the methodology used in EF calculations is stabilizing (GFN 2005) and EF scholars are formalizing a research agenda (Kitzes*, et al.* 2007). Additionally, developments such as employing input-output (I-O) econometric techniques has improved sub-national resolution and enables analysis of the Footprint by social cohorts (McDonald*, et al.* 2006), industrial sectors, consumption categories, and regions (Weidmann*, et al.* 2006). Understanding the export and import of Ecological Footprint may similarly be useful to inform policy discussion.

3. Measuring ecologically unequal exchange

3.1. A method for measuring the Ecological Footprint embodied in trade

The method for calculating the ecological weight of trade flows consists of combining national level EF accounts with the United Nations Statistics Department's COMTRADE global trade database (UNSD 2007). Each of the products[7] in the

[7] At four digits of resolution, the level of detail used in this study, HS02 distinguishes 1245 products.

Harmonized System 2002 (HS02) nomenclature is associated with a Footprint yield coefficient (t/ha). These yield coefficients are derived from the National Footprint Accounts (GFN 2006). The data year studied was 2002. In this study we chose to report results in hectares rather than in global hectares in order to facilitate mapmaking.[8]

The National Accounts provide a robust, detailed accounting of the total Ecological Footprint and total imported and exported Footprints for the most populous 150 countries. The Footprints of raw and embodied resources are summed so that all major natural resource flows are captured. The National Accounts also calculate, for each nation, the Footprint it needs to produce each of a variety of product types. The Accounts primarily track raw resources but offer conversion factors to convert between primary and secondary products (e.g. between oranges and orange juice), on a basis of weight or volume. (Wackernagel, *et al*. 2005)

These Footprint yield factors are gathered in a table we call a Product Land Use Matrix, or PLUM. The PLUM contains for every country, year, and HS02 product code, a yield coefficient (t/ha), how large of a Footprint is exerted on each of the four major land use types (pasture, cropland, forest, and ocean/marine) in the production of that product.[9] Built-up land was assumed to not be 'traded' and was excluded from the analysis. Table 1 shows some representative entries from the PLUM.

Table 1: PLUM Product Land Use Matrix (Footprint Yield Coefficients)

Country	Year	HS02 Code	Product Description	Pasture (t/ha)	Cropland (t/ha)	Forest (t/ha)	Marine (t/ha)
France	2002	H2-0104	Live sheep and goats.	0.18	0.24	0	0
France	2002	H2-0105	Live poultry	2.44	0	0	0
			…				
Germany	2002	H2-0104	Live sheep and goats.	0.25	0.13	0	0
Germany	2002	H2-0105	Fish, frozen, excl. fish fillets	0	0	0	4.90
Germany	2002	H2-1001	Wheat and meslin	0	6.91	0	0
Germany	2002	H2-4701	Mechanical wood pulp	0	0	8.97	0

[8] The two units can be trivially interchanged using the equivalence and yield factors published in the National Accounts. Global hectares are principally useful to compare between Footprint assessments.

[9] The National Accounts break down land use into 10 types, but for simplicity we have condensed them to four in this study. The PLUM could be extended to distinguish among the 10 land uses used in the Accounts.

3.1.1. Constructing a Product Land-Use Matrix (PLUM)

Ideally one output of the National Accounts would be a list of per-product Footprint intensities. These data would directly comprise the PLUM. However, the National Accounts 2006 Edition (the most current version at time of writing) offers these data in a different product nomenclature (SITC rev. 3) than that used by COMTRADE (HS02). The forthcoming 2008 Edition of the Accounts will be recoded using HS02 nomenclature. Therefore, one challenge in the implementation, though not conceptualization, of this study was producing a PLUM in HS02 nomenclature. To build a complete, HS02-coded PLUM we utilized the same source data and applied similar methodology used in the National Accounts but tagged products by HS02 code rather than SITC code. Sections 3.1.3 through 3.1.7 detail the data and methodologies used to fill the PLUM.

3.1.2. Integrating COMTRADE and the PLUM

To arrive at Footprint flows, the trade flows in COMTRADE, recorded in tonnes, are cross multiplied by Footprint yield coefficients. This results in a full bilateral trade dataset reporting the number of hectares traded between countries. The National Accounts as published are trade-adjusted but report only total imports and exports, not disaggregated by trading partner. In this study we start with the non-trade-adjusted Footprint of production, as calculated by the National Accounts, and apply the production yields to exports and imports.

In the COMTRADE dataset 13% of records, representing 26% of total trade value, had no weight values reported. Since all the Footprint yield coefficients are in units of weight, the missing weights were filled, using price ($/t) estimates. For each commodity two reference prices were calculated. The World Price (WP) was calculated as the mean price paid by all nations at import or export of each commodity. (Transactions below 50kg were excluded from the calculation of the WP to filter reporting errors where a reporter filled in weight in tonnes instead of kilograms or in number of units rather than weight.) Secondly, an Average Reference Price (ARP) and Median Reference Price (MRP) were calculated as the mean and median prices paid at import/export by a reference group of eight major countries (France, Germany, Italy, Mexico, Spain, Sweden, UK, USA). Where the WP and the MRP differed by <50%, the World Price was used. If the WP and the MRP diverged by > 50%, but Reference Prices (ARP and MRP) differed by <50%, then the MRP was used. In 117 product categories (representing 11% of the total traded value), where <10% of the value of trade in those products had no weight data but the three price measures disagreed substantially, the WP was used. Finally, for the remaining 32 categories where the three price measures disagreed substantially and where >10% of the trade value required price-estimated weights, prices were manually estimated by comparing the WP and the prices paid by the eight countries comprising Reference Price group. Two commodity codes, Artworks (H2-97) and Commodities Not Specified According to Kind (H2-99) were assigned weights of 0 kg, omitting them from the calculations.

The following sections 3.1.3 to 3.1.7 describe how the PLUM was filled. These calculations yield less accurate results than the National Accounts can provide. These results must be recognized as approximations until a new edition of the Accounts using HS02 coding is available.

3.1.3. Forest Product Yield Coefficients

Timber yields are the basis for calculating how much forest area each country requires to produce a tonne of forest products. Three sets of national timber yields were available. The first is from the FAO Global Fibre Supply Model (GFSM) study (FAO 2000). These data report each country's average forest increment, in m^3 roundwood/ha/yr. The second yield set is based on the IPCC recommended methodology for estimating national forest growth (IPCC 2006). GFN executed the IPCC methodology to calculate a second dataset of timber growth. The IPCC method suggested generally higher timber yields than did the GFSM. Both of these two yields estimate the annual timber increment. However forests may (and often are) harvested to produce a yield greater than their annual increment, causing deforestation. Using FAOSTAT ForestSTAT data (FAO 2001) we estimated a third true 'production yield' by dividing the annual FAO-reported timber production (m^3) by the FAO-reported forest area (ha). The 'production yield' approach is the chosen approach, except in the cases of missing/unavailable values in which case the GFSM, or if unavailable, the IPCC, data were used. Overall the chosen production yield approach agrees within reasonable limits to the GFSM results. 70% of the national data points differ by ≤33% and 95% differ by ≤66%. The chosen approach suggests more extensive forest use: for 73% of the countries, the chosen approach indicates more forest area is used to harvest timber products than is suggested by the GFSM. For three outlier countries (Brazil, Russia, and Canada) we used the GFSM estimate, since the production yield estimate was unreliable given their vast forested areas, leading to very high estimates of deforestation. To convert between timber products, reported in tonnes, and raw timber, counted in volume (m^3), a set of Technical Conversion Factors (TCFs) from an EU FAO study (UNECE/FAO 2005) were used as the basis for estimating the amount of roundwood (m^3) required to produce one tonne of each HS02 product. Countries with missing yield data were assumed to have world-average timber yield. Three validation filters were applied to the yield data. First, a check for erroneously low yields was performed: if the net yield was below 30% of the world average net yield, the world average figure was used. Second, a cap, set at 10 times the world-average yield, was applied to constrain outliers. Finally, since HS02 nomenclature does not distinguish between natural and synthetic rubber, and natural rubber is a low-yield, area-intensive product, a manual filter was applied to set the forest footprint yield of rubber to 0 in countries which do not produce natural rubber.

3.1.4. Marine Product Yield Coefficients

Aquatic products are produced from aquaculture, fishing within a country's EEZ, and from deep sea fishing. The Footprint of fish caught in the open ocean is considered part of the production Footprint of the nation recording the landed catch. The HS02 nomenclature has only seven categories to distinguish marine products. Because of this low resolution it was not possible to calculate the trophic level of exported fish products, an important step for arriving at an accurate fish footprint. Repeating the calculations at six-digit HS02 resolution and adjusting for the trophic level of each species would improve the accuracy of the findings. As a proxy a world-average marine product yield was used. The global fish catch of 93 Mt was divided by an estimated fished area of 19 M km^2 to arrive at a marine product yield of 4.9 t/ha. These data points are taken from the National Accounts. The yields for three product codes of high-quality fish ready for human consumption[10] were adjusted downward by a factor of 2, to 2.5 t/ha, to account for the high trophic level of these products. A factor two adjustment is a conservative estimate since the yield of high trophic-level fish can be as much as an order of magnitude lower that of low trophic level fish.

3.1.5. Cropland Product Yield Coefficients

Production yields (kg/ha) for each country and each crop product were taken from FAOSTAT (FAO 2001). FAOSTAT product categories were mapped to HS02 categories. Where multiple FAOSTAT categories matched a single HS02 category (e.g. Apples and Pears are separated in FAOSTAT but a single category in 4-digit HS02 nomenclature), the average of the matching categories was used to estimate the yield for the HS02 product. A simple world-average yield was calculated for each product. HS02 categories with no directly matching FAOSTAT category were assigned averages of similar products. Daughter products (e.g. orange juice) were assigned the yield coefficient of their parent product (oranges), plus in some cases a dilution factor to increase the yield where the weight of the daughter product was augmented beyond the simple parent product. Countries with incomplete yield data were filled in with world yields. A check for erroneously low yields was performed: if the yield of a particular crop in a country was less than 30% of the world average yield, the world average figure was used.

---

[10] The three products were: Live fish (HS02-0301), Fish, fresh or chilled, excluding fish fillets (HS02-0302), and Fish, frozen, excluding fish fillets (HS02-0303).

3.1.6. Pasture Product Yield Coefficients

The Footprints of animal products are among the most difficult to calculate for a number of reasons. Animals are raised on a combination of open range grazing and fed harvested grasses as well as concentrate feed (primarily from grains such as corn but also from fishmeal and animal fats). Animals' diets vary dramatically by country: a cow raised in an industrialized nation could be fed entirely on concentrate feed and consume as much as 10 times as much food over its lifetime than a cow eating grass and other foraged food in a less developed country (Steinfeld and de Haan 1997). Data on range productivity are scarcer than data on crop farming and forestry. Since pasture areas vary seasonally and blend in with sparse forests in land use classification efforts, different land use datasets vary dramatically in reporting how much pasture area a country has. Additionally, there is an open methodological question which remains as yet unsettled by the Footprint research community: In a given year, 100% of a pasture area may be available for grazing, and covered in cattle footprints, but less than 100% of the available grass is consumed. Should the Footprint calculation include just the grass consumed, or the entire area disturbed? (Lenzen, *et al.* 2007, Lenzen and Murray 2001) Collectively, these difficulties are particularly relevant for countries with extensive grazing operations, such as Australia, Mongolia, South Africa, Brazil, New Zealand, Argentina, and the United States.

The Global Footprint Network is in the process of re-evaluating the Footprints of animal products as part of the next edition of the National Accounts. For this study estimates of pasture product yields were derived from the existing National Accounts. These estimates are very likely accurate to within a factor of 5, and possibly accurate up to a factor of 2. Where estimates and assumptions were made they were intentionally biased toward under-estimating the true Footprint area. As a result, the pasture Footprints of most countries are visibly under-estimated. For example, with the yield coefficients used, Australia exports a mere total of 38 million hectares of pasture, or 5% of its total land area, while in fact sheep stations alone cover 12% of its total land area producing mutton and wool almost exclusively for export.

3.1.7. Energy Footprint Coefficients

One land use was calculated separately, namely, the energy footprint. Energy Footprints consist of the land area inundated by hydropower dams, a Footprint of nuclear power (currently set at par with fossil fuel energy, for lack of a consensus on an alternate methodology; see Kitzes *et al.* (2007) for discussion), and a CO_2 footprint used in generating energy used in a nation. The EF methodology presently accounts for CO_2 pollution by calculating the area of forest necessary to sequester the CO_2.[11]

Nations which import embodied CO_2 in energy-intense products do not physically exert their carbon footprint on the providing nation but rather on the global commons. Thus the resulting Footprint cannot be said to be literally exerted on that nation.[12] Energy Footprints are reported separately from actual land uses (cropland, forest, etc.) so as to not exaggerate the land area used in a trading partner. This study assumed that all embodied energy came from a national-average fuel mix. The Footprints of fossil fuel and nuclear generated energy were not distinguished from hydropower and renewable sources.

Embodied energy estimates (GJ/t)[13] for each HS-02 product were gathered. The primary source for these figures was the embodied energy estimates, in SITC nomenclature, in the National Accounts. These data are maintained in an in-house library at GFN in turn originally based on LCA-based data gathered by Stockholm Environment Institute–York (Barrett and Weidmann 2005) and the Centre for Energy and Environmental Studies (IVEM) at University of Groningen. When translating the embodied energy figures from SITC to HS02, where the two nomenclatures did not have an exact correspondence estimates based on similar products were used. From the embodied energy estimate, in GJ, national carbon intensity data from IEA (2004) (g CO_2 /kWh) were used to translate energy into estimated CO_2 emissions. Estimating embodied energy and carbon in products remains a difficult exercise. The findings of this study are not claimed to be authoritative – an approximate error range within ±50% is likely – but are intended to be used as a point of comparison for other estimates to move closer to accurate values. For a comparison to Ahmad and Wyckoff's results see section 4.2.4 and refer to (Weidmann, *et al.* 2007, esp. Table 1) for an overview of recent studies on the topic of embodied CO_2.

3.2. Limitations

Footprint trade flows can be calculated either using a footprint coefficient approach or using I-O methodology. One drawback to a coefficient approach is that unless the

---

[11] This approach is chosen as the most conservative of reasonable approaches for calculating the Footprint of CO_2 pollution. For more on the rationale behind this, and summaries of the debate over the merits and flaws of this approach, the reader is referred to (Global Footprint Network 2005).

[12] The exceptions are for hydropower and renewable energy, where the Footprint of energy production is physically in the producing nation. This study ignores these non-CO_2 energy footprints. Approximately 88% of global energy demand used to produce traded products is currently fossil-fuel based. Hydro, nuclear, and renewable sources were omitted for simplicity.

[13] Only energy expended in harvesting, processing, and transporting products are included. This differs from the eMergy approach in which embodied solar energy (in wheat, for example) is included. Including the embodied solar energy would be double counting in Footprint terms, since wheat would have a Footprint both for the cropland it grew on and again for the sun energy that fell on that cropland.

coefficients are calculated very carefully the sum of the Export Footprint from the resulting dataset may not equal the Export Footprint as calculated in the National Accounts. (Conceptually if the complete PLUM is generated from National Accounts this risk is avoided, but given that the Accounts are generated primarily from raw resource accounts and the PLUM entries code more processed child products this is difficult to ensure.) An I-O approach guarantees no sector of the studied economies is omitted. An I-O approach is also better suited to analysing international production chains where products are transformed. A coefficient approach determines the net export footprint by subtracting the total export footprint from the import footprint, but cannot disaggregate by individual products. Finally, an I-O approach has the benefit of capturing the trade in services between countries, which is omitted in the coefficient approach.

The advantages of a coefficient approach over an I-O approach are several: Principally, I-O tables are available for fewer countries than National Accounts cover so global trade analysis is currently not possible using I-O methods. Second, I-O analysis can only be conducted when both trading partners have I-O tables whereas Footprint coefficients can be applied to movements of individual products at any resolution from household to municipal to national. This would be useful in calculations of household and sub-national footprints assessments (Wackernagel, *et al.* 1999, Wackernagel and Richardson 1998). Finally, most I-O tables are available in only monetary and not physical units, forcing researchers to make assumptions of proportionality between monetary and physical flows (Lenzen 2001, Weisz and Duchin 2006).

The principle limitation constraining the accuracy of this study was that the PLUM should be filled using the National Accounts. Since the Accounts were not available in HS02 nomenclature compatible with COMTRADE at the time of this study, the Footprint yield coefficients in the PLUM had to be calculated using the data sources and methodology of the Accounts. The result is that the PLUM data used are less accurate than would be if produced by the National Accounts. This deficiency can be surpassed by repeating the study when an HS02-coded edition of the Accounts is available. Producing an HS02-coded National Accounts is itself a challenging project. The source data for the Accounts primarily report on raw natural resources. The HS02 classification is designed to record international trade flows and tends to utilize categories for more highly processed child products.

A second major limitation of the study, revealed by analysis of the results, is that the estimates of embodied CO_2 are highly problematic. See section 4.2.4 for a discussion. Future refinements of this work must better address the issue of embodied CO_2.

The accuracy of this study is also constrained by the accuracy and completeness of the COMTRADE dataset. One potential source of error is incomplete reporting. A number of countries do not report to the COMTRADE database in HS02 nomenclature. For these countries we inferred their imports and exports by examining the partner records of those countries which did report to COMTRADE. Only 88 countries report in HS02 nomenclature, and the 62which do not were estimated using this implied trade method. Fortunately, they do not appear to substantially affect the findings. The sum of reported versus implied imports and exports agreed within 5% (in units of both hectares and dollars) for the 88 reporting countries. The 88 reporting countries account for ≈90% of the total value of international trade in monetary terms. See *Appendix A:* COMTRADE Reporting Nations for a list of which nations reported trade and which were inferred.

A future direction of study using the PLUM could be to produce a timeseries. Data in the National Accounts and COMTRADE are available as far back as 1962 (Wackernagel, et al. 2004), and a PLUM with a time dimension could be constructed. One major difficulty in executing this is that the dominant nomenclature used in COMTRADE reporting shifts over time, through three SITC and three HS revisions. Normalizing COMTRADE into a single-nomenclature timeseries poses a practical challenge.

4. Results & Discussion

4.1. Discussion of key findings

The primary intention of this paper has been to motivate and introduce the PLUM methodology. The full dataset of results will require further work to analyse. This section offers a first order, preliminary analysis of the results by testing several example hypotheses regarding the patterns of international ecological resource trade. The overarching question the answer to which are attempting to illuminate with these tests is: do the wealthy countries of the North disproportionately appropriate natural resources from the poorer nations of the South?

The summary tables in this section separate the energy Footprint and the land-area footprint. Footprint flows are reported in hectares (ha) and not the traditional units of global hectares (gha) used in most other Footprint studies. For this study the decision was made to keep results in actual hectares so they could be compared to actual land availability in exporting nations. Hectares can be trivially normalized to gha using the National Accounts.

Table 2 summarizes the results by top-level HS02 categories. The results observed are expected. Machinery and automobiles are the most valuable traded products, and mineral products the heaviest. Weighted in Footprint terms natural resources are the dominant flows. Note that several categories show a Footprint of zero. This is due to the fact that in constructing the PLUM there were insufficient conversion factors to determine the Footprint of many highly manufactured products. This bias results in an underweighting of the Footprint of those items. However the areal Footprint of most of these products is negligible, and areal extent of their impact on the biosphere small in comparison to biological resources. Weighting by CO_2 generally agrees with the monetary value.

4.1.1. Does the 'Rich's Footprint rest on 'Poor' nations?

One of the frequently cited claims in von Weizsäcker, Lovins, and Lovins (1995) is that 20% of the world population, mainly in the North, is appropriating 80% of the world's natural resources. This conclusion is based on material flow analysis. If this conclusion were true one would expect to find the balance of trade flowing toward that exclusive 20%.

We define two groups of nations. The 'Rich' nations are those 48 countries home to the 20% of the world population with the highest per capita GDP (collectively comprising 85% of global GDP). The remaining 102 nations are the 'Poor'. Figure 1 illustrates the trade balance between the two groups in terms of monetary value, weight, and Footprint. Table 3 provides a similar analysis using High, Middle, and Low Income classification, as defined by World Bank.

Overwhelmingly, the 'Rich' nations trade amongst themselves. By all three measures in Figure 1, ≈75% of the imports to the 'Rich' nations are from other 'Rich' nations. Table 3 repeats this finding: High income nations source 65% of their imports from other High income nations. The 'Poor' nations source more imports from the 'Rich' than from the 'Poor'. This too is repeated by Table 3: Low Income nations import >75% of their (small) Footprint imports from High and Middle income nations.

The 'Rich' countries occupy only 29% of the earth's surface area but trade predominantly amongst themselves. This does not appear to support the contention that the 'Rich' use 80% of the world's resources. This contention could be true if the 'Rich'-controlled third of the planet were disproportionately well endowed with resources, or if the 'Rich' were using natural resources in ways that do not appear in recorded trade flows.

The results do not appear to support the hypothesis than natural resources flow predominantly from less developed regions to more developed regions. North America and Europe are the source of 42% of Footprint exports to all countries. Less developed regions export much less Footprint than do more highly developed regions (see Table 8). If anything the 'Poor' appear to appropriate from the 'Rich'.

Table 2: Total Footprint, Value, Embodied CO_2, and Weight, by HS02 Section

HS02 Section	**Value** (bil. USD) Export		**Value** (bil. USD) Import		**Footprint** (M. ha) Export	**Footprint** (M. ha) Import	**CO_2** (Mt) Export	**CO_2** (Mt) Import	**Weight** (Mt) Export	**Weight** (Mt) Import
Sec. I- Animals & Products	$	126	$	133	88	104	261	280	68	71
Sec. II- Vegetable Products	$	139	$	150	19	18	486	475	462	459
Sec. III- Organic Fats and Oils	$	23	$	24	-	-	107	105	45	45
Sec. IV- Prepared Food	$	191	$	199	3	3	2,230	600	1,069	311
Sec. IX- Wood & Fiber Products	$	72	$	75	43	38	322	311	402	282
Sec. V- Mineral Products	$	629	$	673	-	-	2,369	2,417	5,436	5,347
Sec. VI- Chemicals	$	540	$	586	-	-	1,742	2,333	420	515
Sec. VII- Plastics & Rubber	$	257	$	268	0	0	1,181	3,459	184	458
Sec. VIII- Hides & Leather	$	53	$	54	-	-	22	40	7	10
Sec. X- Wood Pulp & Paper	$	146	$	151	6	7	676	1,408	194	308
Sec. XI- Textiles	$	378	$	380	4	4	1,202	1,666	67	91
Sec. XII- Misc. Dress Accessories	$	57	$	64	-	-	27	36	5	5
Sec. XIII- Stone,Cement,Ceramic,Glass	$	71	$	72	-	-	208	232	104	109
Sec. XIV- Pearls and Jewels	$	117	$	121	-	-	5	8	0	1
Sec. XIX- Armaments	$	6	$	5	-	-	3	2	0	0
Sec. XV- Base Metals	$	390	$	401	-	-	3,144	7,493	562	926
Sec. XVI- Machinery	$	1,826	$	1,843	-	-	4,090	18,563	197	827
Sec. XVII- Vehicles	$	792	$	768	-	-	1,738	1,918	144	158
Sec. XVIII- Precision Instruments	$	218	$	225	0	0	454	3,856	16	123
Sec. XX- Mis. Mfg. Articles	$	145	$	164	12	10	474	532	58	59
Sec. XXI- Art & Antiques	$	169	$	166	-	-	-	-	-	-
Total	**$**	**6,345**	**$**	**6,518**	**176**	**185**	**20,741**	**45,734**	**9,442**	**10,105**

Figure 1: Imports to the 'rich' and to the 'poor', by source and by metric

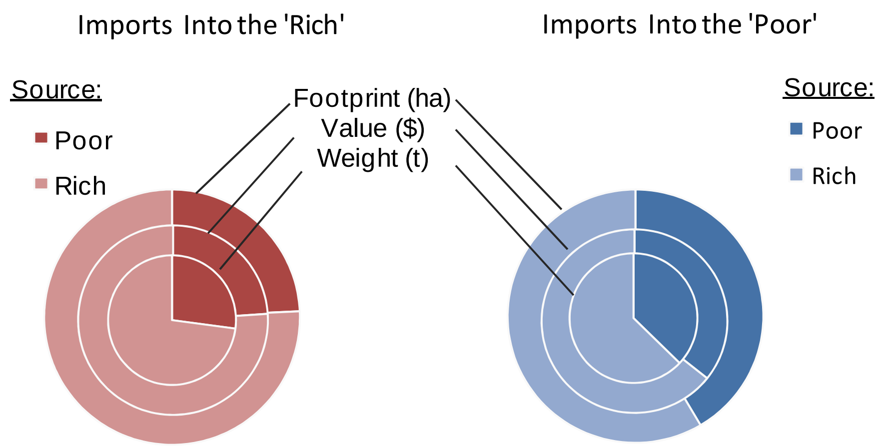


Table 3: Comparison of Footprint and monetary imports (grouped by income bracket)

Footprint Imports (M ha), by GDP bracket

Imports Into:	Source: High Income	Low Income	Middle Income
High Income	206	15	95
Low Income	9	5	7
Middle Income	124	17	76
Grand Total	**339**	**36**	**178**

Monetary Imports (B USD), by GDP bracket

Imports Into:	Source: High Income	Low Income	Middle Income
High Income	9,676	13	2,321
Low Income	337	4	85
Middle Income	3,817	7	876
Grand Total	**13,830**	**24**	**3,282**

4.1.2. China's largest source of raw resources is Africa?

China has been called 'the world's factory'. A widely accepted hypothesis is that the country imports raw materials from abroad – importantly, from Africa–and manufactures these into resources into goods for export to Western markets. Using the results of this study we test this hypothesis.

Table 4 shows China's trade in Footprint and MFA terms with each world region. In Footprint terms China has an even trade balance with Africa, though in MFA terms China's imports from Africa exceed exports to it by a factor of 6. Table 5 drills down to look at China's top imports from Africa. By weight oil imports dominate, and by Footprint, wood products dominate. Approximately 13% of China's oil imports come from Africa.

The hypothesis that China predominantly imports from Africa and exports to the West is not supported by these results. In MFA terms Africa provides only 7% of China's imports, and in Footprint terms even less (<3%). In terms of exports, together North America and Western Europe receive 22% of China's exports by Footprint and only 4% by weight. We may conclude that in physical terms Africa is not a key import source for China, and exports to Western markets are just a fraction of those to the regional Asian market. China's trade in physical terms is predominantly regional, not global.

Table 4: China's Inter-Regional Trade

China, 2002	**Exports To**	**Imports From**
Footprint (M ha)		
Africa	0.6	0.6
Asia-Pacific	6.7	9.7
Latin America	0.3	3.0
M. East & C. Asia	1.1	1.2
North America	1.7	6.5
Other Europe	0.1	0.0
Western Europe	0.8	0.6
Tonnage (Mt)		
Africa	5.0	29.1
Asia-Pacific	959.4	192.7
Latin America	10.8	50.9
M. East & C. Asia	8.4	77.3
North America	26.4	34.5
Other Europe	1.3	4.1
Western Europe	23.1	17.1
Other*	84.2	18.8

** See footnote 14.*

Table 5: China's Top 5 Commodity Imports from Africa, by weight and Footprint

HS02 Code	**Commodity** (2-digit resolution)	**Weight** (Mt)			**Footprint** (1000 ha)
H2-27	Mineral & oils	14.9	H2-44	Wood and manufactures	537
H2-26	Ores, slag and ash	11.5	H2-52	Cotton	20
H2-44	Wood and manufactures	0.8	H2-51	Wool	18
H2-72	Iron and steel	0.5	H2-18	Cocoa	17
H2-25	Salt; sulfur; earths and stone	0.4	H2-53	Vegetable textile fibres	15

[14] The "Other" group is comprised of very small nations which have poor data availability and do not have a significant share of global trade. It also includes China Macao SAR, and contains trade records from COMTRADE where only a region (e.g. "Other Asia, nes [not elsewhere specified]") and not a specific trade partner is reported. Footprint values are not calculated for countries in the "Other" group.

4.1.3. Is Sweden is a net importer of Footprint from Denmark?

A common query of the results will be to ask what is the ecological balance of trade between two countries. For example, what is the net Footprint trade balance between Sweden and Denmark? Table 6 presents the answer to this query on the results. By weight and monetary value, Sweden is a slight net importer from Denmark. But in Footprint terms Sweden is a net exporter to Denmark. Of those exports, 55% is forest Footprint, and of its imports from Denmark 80% is cropland Footprint. This provides a clear example of two countries specializing in their ecological comparative advantage and trading.

Table 6: Trade Between Sweden and Denmark

Reporter	**Flow**	**Partner**	**Weight** (Mt)	**Value** (B. USD)	**Footprint** (ha)
Sweden	Exports To	Denmark	6.1	$5.1	243,266
Sweden	Imports From	Denmark	8.5	$6.1	154,947
	Net Imports		*2.46*	*1.03*	*(88,319)*

4.1.4. Exports from poor nations are more land intensive than from others?

The process of capital accumulation should mean developed nations will achieve higher economic output per unit of natural capital input. We may test this hypothesis by comparing the total value received from exports to the embodied natural capital (Footprint) in those exports (see Table 7). The results observed are expected: High Income nations receive a median ratio between monetary and Footprint value over five times greater than that achieved by Low Income nations. Exports from Low Income nations are more land-intensive, and exports from Middle and High Income nations are more labour and capital intensive.

Table 7: Price paid for Footprint imports by 'Rich' vs. 'Poor'

Price of Imports ($1000/ha)

	Source:		
Destination:	**High Income**	**Middle Income**	**Low Income**
High Income	$ 16	$ 13	$ 7
Middle Income	$ 7	$ 4	$ 2
Low Income	$ 10	$ 6	$ 1
Median	*$ 10.0*	*$ 5.9*	*$ 1.7*

4.1.5. What are the largest inter-regional Footprint trade flows?

Table 8 summarizes the direct Footprint flows between regions.[15] Three of the four largest trade volumes are intra-regional. The largest interregional flows are from Latin to North America, and from North America to Asia-Pacific. Another surprising finding is that Western Europe imports from abroad only half as much Footprint as does North America (though this could be a distortion due to the enormous trade between US and Canada).

Table 8: Imports of Ecological Footprint between Regions

Footprint Imports (M ha), by geographic region

Destination:	Source: Africa	Asia-Pacific	Latin America	M. East & C. Asia	North America	Other Europe	Western Europe
Africa	3.0	2.3	0.1	5.1	0.9	0.5	11.7
Asia-Pacific	5.7	63.0	6.3	12.8	22.4	1.1	11.5
Latin America	3.9	9.1	14.1	5.6	16.3	1.0	14.4
M. East & C. Asia	6.6	3.5	0.2	13.8	0.5	1.9	7.9
North America	5.8	41.1	61.9	5.1	57.2	0.4	7.3
Other Europe	1.1	0.6	0.1	9.8	1.0	11.3	20.4
Western Europe	3.3	5.7	1.1	7.5	2.3	4.5	60.7
Grand Total	**15.9**	**110.6**	**78.0**	**100.5**	**133.9**	**50.9**	**16.2**

4.2. Comparison with Other Studies

4.2.1. Comparison with Andersson and Nevalainen: Finland

Andersson and Nevalainen (2003) performed a Footprint trade balance accounting for Finland using a similar Footprint coefficient approach as used in this study. As shown in Table 9 our results match Andersson's findings within a factor of two in most cases.

The difference in results is primarily explained by the fact that the Footprint yield coefficients used by Andersson and Nevalainen differ from those used in this study. Andersson's coefficients are based on earlier versions of the National Accounts

[15] The table reports Import flows. Due to data asymmetry in COMTRADE, reported import flows do not precisely match the reported inverse export flows. In aggregate the asymmetry is <4% but in individual cases it may be as much as 30%. This discrepancy is intrinsic to the COMTRADE dataset. We chose to report import flows rather than export flows or attempt to reconcile the two.

spreadsheets.[16] The yield coefficients used in this study are from a more recent version. The other source of difference comes from using two slightly different trade datasets. Andersson and Nevalainen used year 2000 data in SITC nomenclature from Finnish Customs, while this study used 2002 data in HS02 nomenclature from COMTRADE.

Table 9: Example for Finnish Footprint trade: Andersson's vs. Moran's findings

Summary: Andersson & Nevalainen (2003)

	Export	Import	Net Export
World	35,428	32,539	2,890
OECD	26,730	16,871	9,859
Rest of Europe	2,559	12,190	-9,630
Dvlping Cntries	5,283	1,342	3,914
EU	13,916	10,972	2,945
North America	2,128	542	1586
North Africa	995	13	983
Rest of Africa	163	100	64
Africa	1,158	113	1,047
Oceania	251	105	146
Rest of Asia	4,323	1,307	3,015
Asia-Pacific	4,574	1,412	3,161
Middle East	669	9	660
South America	283	131	152

Units: 1000 gha

Present Study

	Export	Import	Net Export
World	30,576	22,746	7,830
OECD Countries	25,751	12,396	13,355
Western Europe	21,413	9,746	11,667
Other Europe	2,019	2,935	-916
Europe	23,432	12,681	10,751
Low Income	194	199	-5
Middle Income	5,609	11,380	-5,771
Dvlping Cntries	5,803	11,579	-5,776
EU-15 Countries	20,470	9,678	10,792
All EU Countries	22,711	12,495	10,216
North America	2,146	608	1,538
Africa	456	174	281
Asia-Pacific	1,739	2,334	-595
M. East & C. Asia	2,434	6,194	-3,760
Latin America	370	754	-384

Categories in italics are sums inserted to facilitate comparison

[16] Andersson took yields from the Living Planet Report 2000; a 1994 early Footprint study for a Swedish county developed by Wackernagel and Lewan; and the results of a 1999 study by Hakanen on the Footprint of a Finnish municipality.

4.2.2. Comparison with van Vuuren et al (1999) : The Netherlands

van Vuuren *et al.* (1999) performed an assessment of the ecological footprint of four countries for 1994, before robust National Accounts were published. Their study was one of the first to calculate embodied Footprint in trade. Their study used the same approach as here, finding Footprint yield coefficients for imports and exports and applying them to Dutch trade statistics. van Vuuren found that the Netherlands used an area 3 to 4 times the size of the Netherlands itself in imported Footprint (omitting energy). Our findings, for the year 2002, indicate a slightly smaller foreign Footprint at 2.5 times the area of the Netherlands.[17]

In terms of CO_2 emissions van Vuuren found that in 1994 Dutch domestic CO_2 emissions were 11.2 Mt CO_2/cap, and adjusted for trade, 8.9 Mt CO_2/cap. We found in 2002 Dutch domestic emissions were 14.5 Mt CO_2/cap,[18] and adjusted for trade, 9.9 Mt CO_2/cap. The two results are substantially in agreement, and given the 8-year difference in measurement periods it is impossible to say whether the difference arises from differing methodology, data, or changes in the trade balance.

4.2.3. Comparison with (Weisz 2007): Southeast Asia

Weisz (2007) cites a recently completed a MFA study (unpublished) which found that "all investigated countries (Laos, Vietnam, the Philippines, and Thailand) were net importers of materials. These countries seemingly do not exploit their raw materials for the world market." Using the Footprint instead of MFA we observe a different result: in Footprint terms the four countries are net exporters, not net importers. This observation underscores the fact that MFA and Footprint analyses can have strikingly different conclusions, as the two tools measure flows differently.

Table 10: Net Exports of Four Southeast Asian Nations

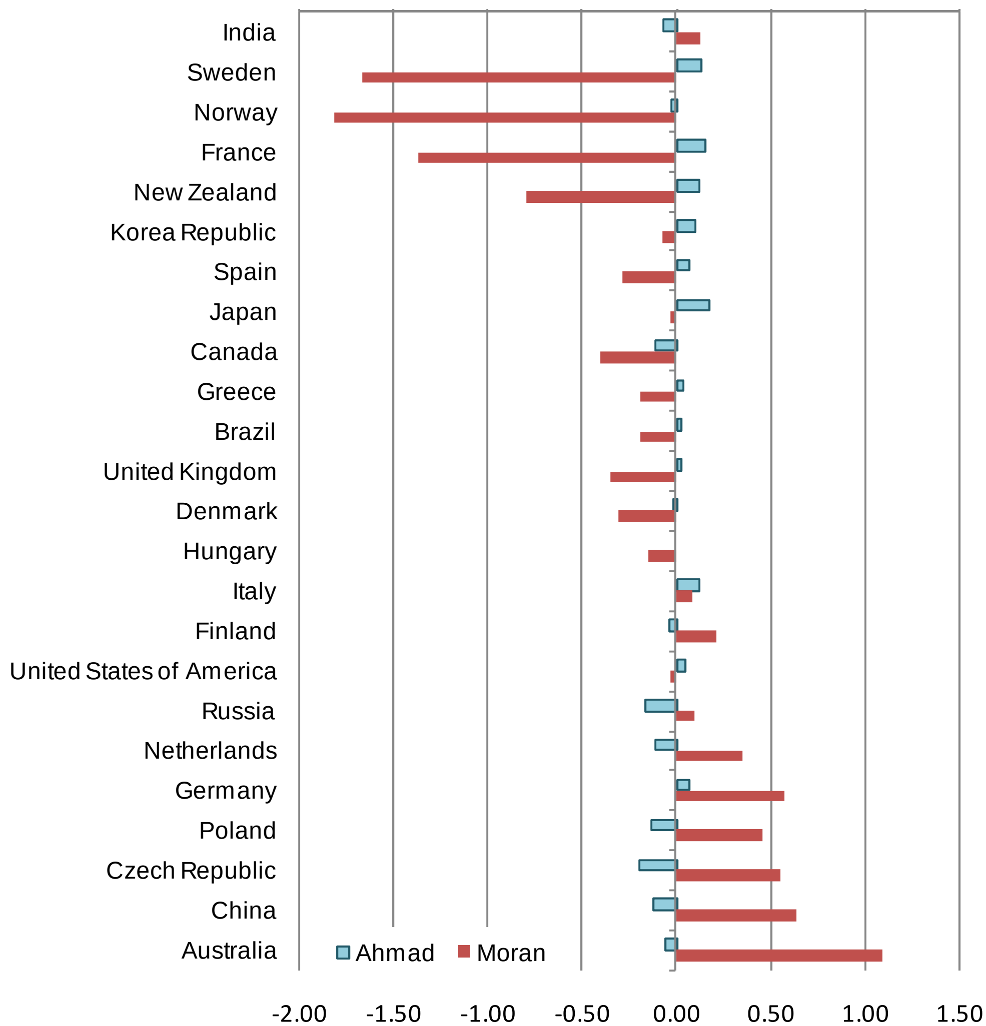
	Value (M $US)	**Weight** (t)	**Footprint** (M ha)
Laos	(316)	*(632)*	0.06
Thailand	3,463	*(10,470)*	8.11
Vietnam	330	5,682	1.19
Philippines	5,409	*(10,659)*	*(2.60)*

[17] The van Vuuren study omitted marine product imports, which our results indicate are negligible for the Netherlands at <0.01 ha/cap.
[18] Domestic CO2 emissions are taken from primarily from IEA (2004) and supplemented with estimates from CDIAC (Marland *et al* 2006) for countries not included in IEA figures.

4.2.4. Comparison with (Ahmad and Wyckoff 2003): Embodied CO_2

Ahmad and Wyckoff (2003) estimated embodied CO_2 emissions in trade for 24 countries, collectively responsible for 80% of global CO_2 emissions. They used a 17-sector I-O trade model combined with the per-sector CO_2 emissions data cataloged by each country. Figure 2 compares our results with those from Ahmad and Wyckoff.

Figure 2: Net CO_2 Imports as % of Domestic Emissions – Moran vs. Ahmad & Wyckoff



The results of the comparison are disappointing. The Moran results show Australia exporting more CO_2 than it emits; obviously incorrect. Because of these implausible results regarding embodied CO_2, in the above analyses the energy Footprint has been generally omitted and only actual land use reported. The culprit is the embodied CO_2 figures. The embodied energy data are based on LCA studies for individual products. Overlapping study boundaries mean it is invalid to sum disparate energy LCA results.

This suggests that embodied energy coefficients should be derived from analyses of a whole economy and not on individual LCA studies.

4.3. Data Visualizations

The COMTRADE dataset of international trade flows contains almost 2.5 million trade-partner tuples. Data visualizations can help analyse these voluminous results. Two complementary styles of maps may be used to visualize the international trade in terms of embodied Footprint. Figures 2 and 3 illustrate the use of flow arrows, where width encodes magnitude, to show the source of all imports to, or exports from, to the selected country. The second style (see Figures 4 and 5) is a 'nighttime lights'-type map which shows, for a given country, the areas around the world where that country's Footprint falls.

4.3.1. Flow Map Visualization

Flow maps effectively depict the movement of objects among geographic locations. Traditionally, cartographers have produced flow maps by hand (Friendly 1999, Minard 1862). This results in attractive maps but is labour intensive. Recently Phan *et al.* (2005) have developed a method for automatically producing flow maps. As a result, we are better able to understand the extent and spatial patterns of trade flows among 150 countries.

Figure 3: The analysis can be conducted on the regional level. This example illustrates the regions from which Western Europe imports biocapacity.

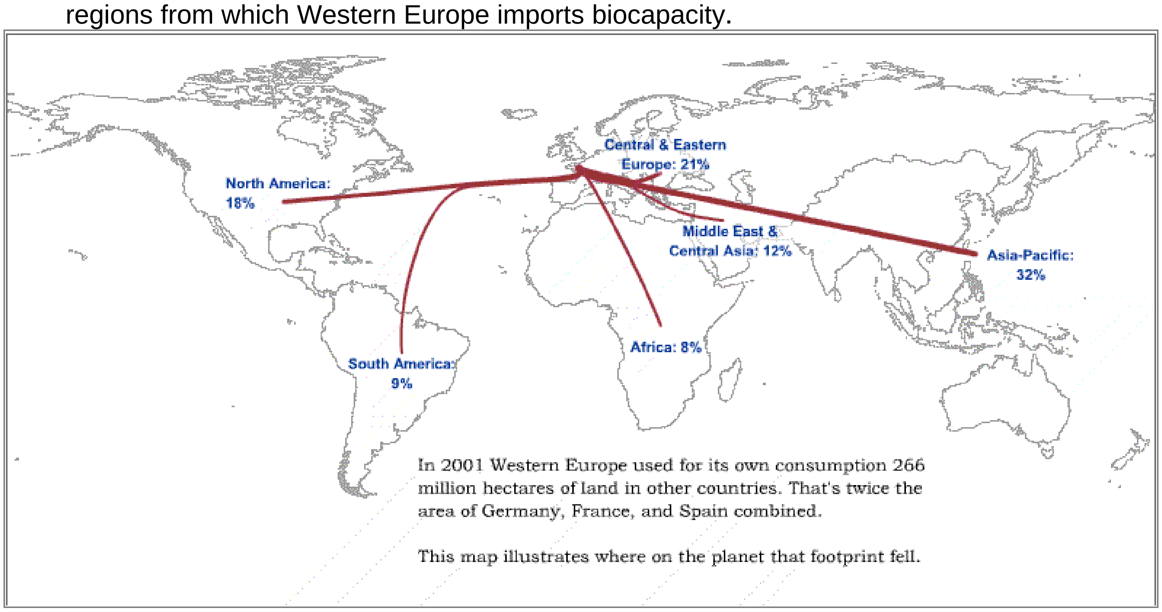


Figure 4: Aggregated imports of ecological good and services into France from its largest trade partners. Units are global hectares. Unlabeled arrows are to the USA, Morocco, and China.

4.3.2. Spatial Analysis Maps

A second style of map to visualize Ecological Footprint of international trade is mapping the land used by imports for a given country using GIS (Figures 4 and 5). This technique combines national Footprint data with global remote sensing data. While it is practically impossible to determine the exact location of production of specific imports, the area used for imports can be attributed to a land-use type within each country. Footprints attributed to forest, pasture, and cropland are represented by green, brown, and yellow coloring, respectively. Land-use types are determined using the Global Land Cover Classification (Hansen, et al. 1998). The Ecological Footprint locations are a weighted random distribution within each country-land type according to the 2002 net primary productivity (NPP) estimates from the Moderate Resolution Imaging Spectroradiometer (MODIS).

In spatially explicit maps the energy footprint (i.e. CO_2 emissions) cannot be mapped directly on to the producing country, since a country's energy footprint of exports could exceed the country's actual land area. We have used a cloropleth fill layer to indicate the amount of embodied CO_2 imported from each trading partner.

Figure 5: USA's Ecological Footprint around the world. Brighter areas represent areas within the countries from which the US imports biological capacity.

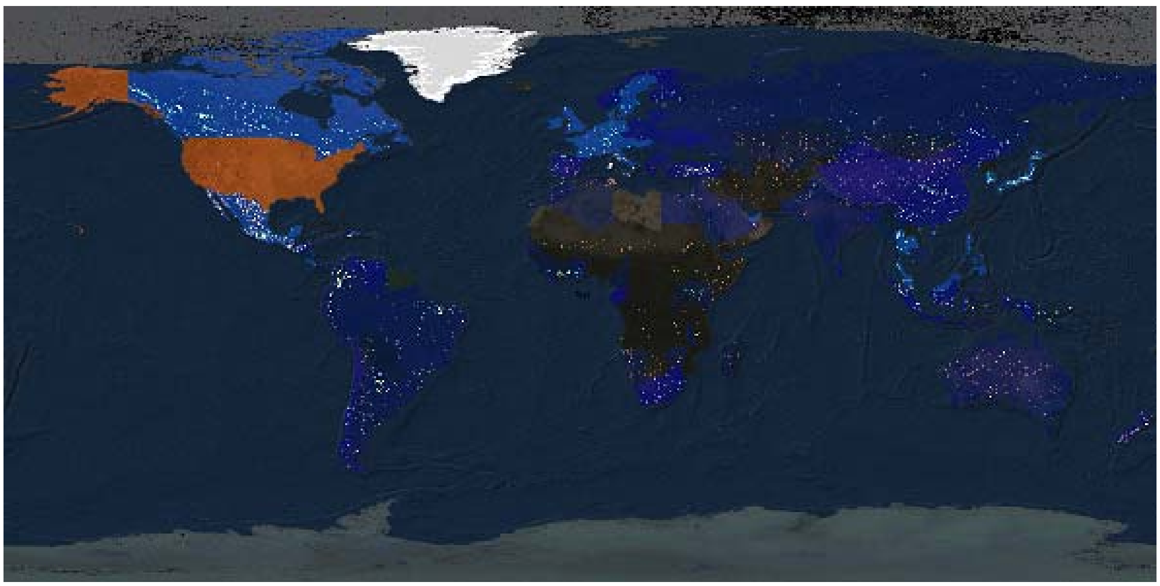
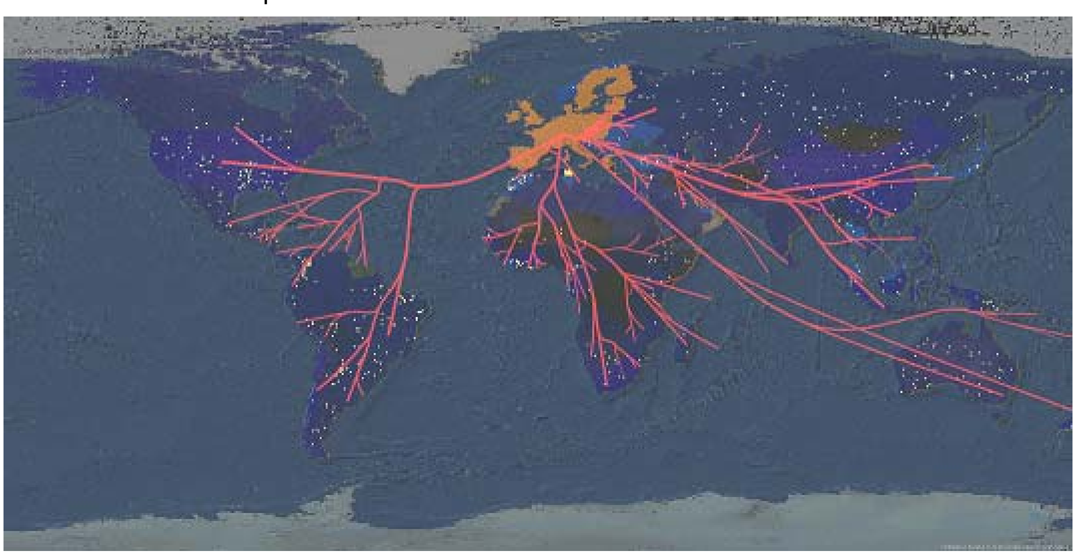


Figure 6: EU's Ecological Footprint around the world, with flow arrows overlaid showing volume and source of imports.



5. Conclusion

Countries' Ecological Footprints fall across the globe. Prices are a weak measure of the ecological value of products. Developing techniques to analyse trade in non-monetary terms is a foundational project of ecological economics. It is also a subject of potential interest by nations interested in biosecurity and taking a stewardship concern for their Ecological Footprint abroad. We have detailed a procedure to calculate international trade flows in terms of Ecological Footprint. Drawing out meaningful information from the data is also a considerable task. We have provided a first-order analysis of the results, finding that the results *prima fascia* appear to not support the hypothesis that the wealthy countries of the North are net importers of biocapacity from the South. We also compared the results to other studies and found general agreement with a similar study using the Footprint, generally differing results from those of MFA studies, and a disappointing finding regarding the proposed method for accounting embodied CO_2 in trade. Finally, we described two visualization techniques – using flow maps and spatial analysis – which can help countries to understand the extent and patterns of their ecological trade relationships.

Much effort in the field of sustainability science has been dedicated to tracing final consumption of goods back to the original points of impact on the biosphere. The method and maps presented here offer a satellite's view, mapping out the major flow circulation patterns across the world. It is a natural complement to individual trace studies, setting context and enabling stronger general conclusions to be drawn.

Knowing the patterns and extent of their ecological trade relationships will help countries understand more clearly their interactions with the biosphere beyond their borders, including revealing ecological burden shifting and negative ecological trade balances. This knowledge can directly inform policy decisions.

Appendix A: COMTRADE Reporting Nations

A number of countries do not report to the COMTRADE database in HS02 nomenclature. Of 248 countries (which include islands and minor territories), 88 report, and 160 do not. Of these 160 countries no Ecological Footprint calculations are available for the smallest 98 bringing the total number of countries under analysis down to 150. For these 62 countries for which we have Footprint figures but not reported trade data we inferred their imports and exports by examining the trade partner records of the reporting nations (that is, where imports arrived from and were sent to, as reported by the 88 reporting nations).

It is impossible to say with analytical certainty how robust these implied values are. Since the true values of trade for the implied countries are not reported it is not possible to validate the estimated values. However the reporting nations are responsible for the majority of world trade and the total value of trade from the inferred nations is likely small. The total monetary value of trade (imports plus exports) of the reporting 88 countries represents approximately $11.2 trillion USD, compared to a total of $1.2 trillion (inferred) from the other 160. This suggests that the implied records comprise <10% of the total value of international trade. Furthermore, using the implied method to calculate the imports and exports of the 88 countries which do report, the total value of reported trade matches the total value estimated by the implied method within ±4%.

The following 88 countries report to COMTRADE in HS02 notation. Trade for all other countries was inferred.

Algeria	Ecuador	Macedonia	Slovenia
Andorra	Estonia	Madagascar	South Africa
Anguilla	Faeroe Islands	Malaysia	Spain
Argentina	Fiji	Malta	Sri Lanka
Aruba	Finland	Mauritius	Suriname
Australia	France	Mayotte	Sweden
Austria	Germany	Mexico	Switzerland
Bahrain	Greece	Mongolia	Thailand
Belarus	Greenland	Morocco	Tunisia
Bel-Lux	Guatemala	Namibia	Turkey
Benin	Guinea	Netherlands	Uganda
Bolivia	Hong Kong	New Zealand	United Kingdom
Brazil	Hungary	Norway	USA
Bulgaria	Iceland	Oman	Uruguay
Burkina Faso	Ireland	Papua New Guinea	Zambia
Canada	Israel	Peru	
Chile	Italy	Poland	
China	Japan	Portugal	
China, Macao SAR	Jordan	Romania	
Colombia	Kenya	Russia	
Croatia	Korea Republic	Samoa	
Cyprus	Latvia	Saudi Arabia	
Czech Republic	Lebanon	Singapore	
Denmark	Lithuania	Slovakia	

References

PDF files for most articles are available online at http://oldspeak.net/eftrade/references/

Ahmad, N. and Wyckoff, A. 2003. Carbon dioxide emissions embodied in international trade. - Organisation for Economic Co-operation and Development (OECD).

Andersson, J. O. and Lindroth, M. 2001. Ecologically Unsustainable Trade. - Ecological Economics 37: 113-122.

Andersson, J. O. and Nevalainen, M. 2003. Unequal Exchange in Terms of Ecological Footprints: The Case of Finland Today. World System History and Global Environmental Change.

Ayres, R. U. 2000. Commentary on the Utility of the Ecological Footprint Concept. - Ecological Economics 32: 347–349.

Ayres, R. U., van den Bergy, J. C. J. M. and Gowdy, J. M. 2001. Strong versus Weak sustainability: economics, natural sciences, and 'conscilience'. - Environmental Ethics 23: 155-168.

Bagliani, M., Ferlaino, F. and Procopio, S. 2003. The analysis of the environmental sustainability of the economic sectors of the Piedmont Region (Italy). - In: Tiezzi, E., Brebbia, C. A. and Uso, J. L. (eds.), Ecosystems and Sustainable Development. WIT Press, pp. 613-622.

Barrett, J. and Weidmann, T. 2005. Embodied Energy Database. Available in GFN 2005. - Stockholm Environment Institute, York.

Bastianoni, S., Pulselli, F. M. and Tiezzi, E. 2004. The problem of assigning responsibility for greenhouse gas emissions. - Ecological Economics 49: 253-257.

Bicknell, K. B., Ball, R. J., Cullen, R. and Bigsby, H. 1998. New methodology for the ecological footprint with an application to the New Zealand economy. - Ecological Economics 27: 149-160.

Bunker, S. G. and Ciccantell, P. S. 1999. Economic ascent and the global environment: World-systems theory and the new historical materialism. - In: Goldfrank, W. L., Goodman, D. and Szasz, A. (eds.), Ecology and the world system. Greenwood Press, pp. 108-122.

Chambers, G (ed),. 2001. Ecological Footprinting: A Technical Report to the STOA Panel. . - Published by European Parliament, Directorate General for Research, Directorate A, The SOTA Programme. Available at http://www.europarl.europa.eu/stoa/publications/studies/20000903_en.pdf.

Chung, H.-S. 2005. Balance of CO2 Emissions Embodied in International Trade: Can Korean Carbon Tax on its Imported Fossil Fuels Make Any Difference in BEET. EcoMod2005 - International Conference on Policy Modelling.

Costanza, R. 1980. Embodied energy and economic valuation. - Science 210: 1219-1224.

Costanza, R. 2000. Forum: The Ecological Footprint. Special Section of Ecological Economics. - Ecological Economics 32: 341-394.

Daly, H. 1996. Beyond Growth: The Economics of Sustainable Development. - Beacon Press.

Daly, H. and Townsend, K. (eds.). 1993. Valuing the Earth: Economics, Ecology, Ethics. - MIT Press.

Dauvergne, P. (ed.). 2005. Handbook of Global Environmental Politics. - Edward Elgar.

Dimaranan, B. V. and McDougall, R. A. 2002. Global trade, assistance, and production: The GTAP 5 data base. - Center for Global Trade Analysis, Purdue University.

Ehrlich, P. R. and Holdren, J. P. 1971. Impact of Population Growth. - Science 171: 1212-1217.

Emmanuel, A. 1972. Unequal Exchange: A study in the imperialism of trade. - Monthly Review Press.

European Environment Agency. 2005. The European Environment – State and Outlook 2005. - OPOCE: Copenhagen.

FAO. 2000. Global Fibre Supply Model. Rome. - Food and Agriculture Organization.

FAO. 2001. FAOSTAT. - Food and Agriculture Organization (FAO), Rome.

Farrow, S. 1995. Extinction and market forces: two case studies. - Ecological Economics 13: 115-123.

Ferguson, L., McGregor, P. G., Swales, J. K. and Turner, K. R. 2004. The Environmental 'Trade Balance' Between Scotland and the Rest of the UK. - University of Stirling, Scotecon.

Ferng, J. J. 2003. Allocating the responsibility of CO2 over-emissions from the perspectives of benefit principle and ecological deficit. - Ecological Economics 46: 121-141.

Fischer-Kowalski, M. 1998. Society's Metabolism: The Intellectual History of Material Flow Analysis. - Journal of Industrial Ecology 2: 61-78.

Foster, J. B. 2000. Marx's ecology: Materialism and nature. - Monthly Review Press.

Frank, A. G. 1966. The development of underdevelopment. - Monthly Review 18: 17-31.

Friendly, M. 1999. Revisions of Minard. - Statistical Computing and Graphics Newsletter 11.

George, C. and Dias, S. 2005. Sustainable Consumption and Production - Development of an Evidence Base, Study of Ecological Footprinting. Final Report -Prepared for Department for Environment, Food & Rural Affairs. Available at http://www.defra.gov.uk/science/project_data/DocumentLibrary/SD0415/SD0415_3232_FRP.pdf.

GFN. 2005. Ecological Footprint Standards v. 1.0 draft 1. - Global Footprint Network.

GFN. 2006. National Footprint and Biocapacity Accounts 2006 Edition. - Global Footprint Network.
Graedel, T. E. and Allenby, B. R. 1995. Industrial Ecology. - AT&T-Prentice Hall.
Grimes, P. and Kentor, J. 2003. Exporting the greenhouse: Foreign capital penetration and CO2 emissions 1980-1996. - Journal of World-Systems Research 9: 261-275.
Haberl, H., Fischer-Kowalski, M., Krausmann, F., Weisz, H. and Winiwarter, V. 2004. Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. - Land Use Policy: 199-213.
Haberl, H., Wackernagel, M., Krausmann, F., Erb, K.-H., Schulz, N. B. and Monfreda, C. 2004. Ecological footprints and human appropriation of net primary production: A Comparison. - Land Use Policy 21: 279–288.
Hakanen, M. 1999. Yhdyskuntien ekologisesti kestävän kehityksen arviointi, kriteerit ja mittaaminen. Suomen kuntaliitto, Helsinki.
Hansen, M., DeFries, R., Townshend, J. R. G. and Sohlberg, R. 1998. Land Cover Classification Derived from AVHRR (1km). - The Global Land Cover Facility.
Heumann, B. 2006. Spatializing Ecological Footprint Imports Using GIS. - In: Moran, D. (ed.). - McGill University Department of Geography. Personal Communication.
Hornborg, A. 2001. The Power of the Machine.
Hornborg, A. 2005. Footprints in the Cotton Fields: The Industrial Revolution as Time-Space Appropriation and Environmental Load Displacement. - Ecological Economics.
Howarth, R. and Norgaard, R. 1992. Environmental Valuation Under Sustainable Development. - American Economic Review 82: 473-477.
Hubacek, K. and Giljum, S. 2003. Applying physical input–output analysis to estimate land appropriation (ecological footprints) of international trade activities. - Ecological Economics 44: 137-151.
IEA. 2004. World Energy Statistics and Balances. - International Energy Agency (IEA) of the OECD.
Imhoff, M. L., Bounoua, L., Ricketts, T. and Loucks, C. 2004. Global patterns in human consumption of net primary production. - Nature 429: 870-872.
IPCC. 2001. Climate Change 2001: Synthesis Report. - In: Watson, R. T. and Team, t. C. W. (eds.). - IPCC, p. 184.
IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. - UN Intergovernmental Panel on Climate Change, pp. Vol. 4, Chap. 4.
Joshi, S. 2000. Product environmental life-cycle assessment using input-output techniques. - Journal of Industrial Ecology 3: 95-120.
Kitzes, J., Wackernagel, M. and 26 co-authors. 2007. A Research Agenda for Ecological Footprint Accounting. International Ecological Footprint Conference (Stepping up the Pace: New Developments in Ecological Footprint Methodology, Policy & Practice).
Lawn, P. 2003. A theoretical foundation to support the Index of Sustainable Economic Welfare (ISEW), Genuine Progress Indicator (GPI), and other related indexes. - Ecological Economics 44: 105-118.
Lenzen, M. 2001. Errors in conventional and input-output-based life-cycle inventories. - Journal of Industrial Ecology 4: 127-148.
Lenzen, M., Hansson, C. B. and Bond, S. 2007. On the bioproductivity and land-disturbance metrics of the Ecological Footprint. - Ecological Economics 61: 6-10.
Lenzen, M. and Murray, S. A. 2001. A Modified Ecological Footprint Method and its Application to Australia. - Ecological Economics 37: 229-255.
Lenzen, M., Pade, L.-L. and Munksgaard, J. 2004. CO2 Multipliers in Multi-region Input–Output Models. - Economic Systems Research 16.
Leontief, W. 1970. Environmental Repercussions and the Economic Structure: An Input-Output Approach. - Review of Economic Statistics 52: 262-277.
Lomborg, B. 2001. The Skeptical Environmentalist: Measuring the Real State of the World. - Cambridge University Press.
Lutz, C., Meyer, B. and Wolter, M. I. 2005. GINFORS-Model. Gesellschaft für Wirtschaftliche Strukturforschung mbH (GWS), Osnabrück, Germany. MOSUS Workshop, IIASA Laxenburg.
Marland, G., Boden, T. A. and Andres, R. J. 2006. Global, Regional, and National Fossil Fuel CO2 Emissions. - Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory, U.S. Department of Energy.
Martínez-Alier, J. 2003. Marxism, social metabolism, and ecologically unequal exchange (draft 30/8/03). World Systems Theory and the Environment.
Matthews, E. and et al. 2000. The Weight of Nations: Material Outflows from Industrial Economies. - World Resources Institute.
McDonald, G. W., Forgieb, V. E. and MacGregora, C. 2006. Treading lightly: Ecofootprints of New Zealand's ageing population. - Ecological Economics 56: 424-439.
McGinnis, M. V. (ed.). 1999. Bioregionalism. - Routledge.

MEA. 2005. Ecosystems and Human Well-Being: Synthesis Report. - In: Island Press (ed.) Millennium Ecosystem Assessment.
Millennium Ecosystem Assessment. 2005. Ecosystems and Human Well-Being: Synthesis Report. - In: Press, I. (ed.).
Minard, C. J. 1862. Des tableaux graphiques et des cartes figuratives. - E. Thunot et Cie.
Monfreda, C., Wackernagel, M. and Deumling, D. 2004. Establishing national natural capital accounts based on detailed Ecological Footprint and biological capacity assessments. - Land Use Policy 21: 231-246.
Mongelli, I., Tassielli, G. and Notarnicola, B. 2006. Global warming agreements, international trade and energy/carbon embodiments: an input-output approach to the Italian case. - Energy Policy 34: 88-100.
Munksgaard, J., Minx, J., Christofferson, L. B. and Pade, L.-L. 2007. Models for National CO2 Accounting. - In: Suh, S. (ed.) Handbook on Input-Output Economics for Industrial Ecology. Springer, Dordrecht; forthcoming.
Munksgaard, J. and Pedersen, K. A. 2000. CO2 accounts for open economies: producer or consumer responsibility? - Energy Policy: 327–334.
Munksgaard, J., Wier, M., Lenzen, M. and Dey, C. 2005. Using Input-Output Analysis to Measure the Environmental Pressure of Consumption at Different Spatial Levels. - Journal of Industrial Ecology 9: 169-186.
Muradian, R. and Martinez-Alier, J. 2001. South-north materials flow: History and environmental repercussions. - Innovation 14: 171-187.
Næss, A. 1989. Ecology, Community and Lifestyle: Outline of an Ecosophy.
Neumayer, E. 2004. Indicators of Sustainability. - In: Tietenberg, T. and Folmer, H. (eds.), International Yearbook of Environmental and Resource Economics. Edward Elgar, pp. 139-188.
Nijdam, D. S., Wilting, H. C., Goedkoop, M. J. and Madsen, J. 2005. Environmental Load from Dutch Private Consumption: How Much Damage Takes Place Abroad? - Journal of Industrial Ecology 9: 147-168.
Norgaard, R. 1989. Three Dilemmas of Environmental Accounting. - Ecological Economics 1: 303-314.
Norgaard, R. 1990. Economic Indicators of Resource Scarcity: A Critical Essay. - Journal of Environmental Economics and Management 19: 19-25.
Odum, H. T. 1971. Environment, Power, and Society. - John Wiley.
Peters, G. P. and Hertwich, E. G. 2006. Structural analysis of international trade: Environmental impacts of Norway. - Economic Systems Research 18: 155-181.
Phan, D., Xiao, L., Yeh, R., Winograd, T. and Harahan, P. 2005. Flow Map Layout. - Proceedings of Information Visualization.
Rees, W. 1992. Ecological footprints and appropriated carrying capacity: what urban economics leaves out -Environment and Urbanisation 4.
Rees, W. E. and Wackernagel, M. 1999. Monetary Analysis: Turning a Blind Eye On Sustainability. - Ecological Economics 29: 47-52.
Schaefer, F., Luksch, U., Steinbach, N., Cabeça, J. and Hanauer, J. 2006. Ecological Footprint and Biocapacity: The world's ability to regenerate resources and absorb waste in a limited time period. - Eurostat, available on line at: http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-AU-06-001/EN/KS-AU-06-001-EN.PDF.
Schmidt-Bleek, F. 1994. Wieviel Umwelt braucht der Mensch? MIPS Das Mass für ökologisches Wirtschaften - Birkhäuser Verlag.
Schutz, Moll, H. and Bringezu, S. 2004. Globalisation and the Shifting Environmental Burden. - Wuppertal Institute.
Schwartz, P. and Randall, D. 2003. An Abrupt Climate Change Scenario and Its Implications for United States National Security.
Shiva, V. 1988. Staying Alive: Women, Ecology and Survival in India. - Zed Press.
Steffen, W., Sanderson, A., Jäger, J., Tyson, P. D., Moore III, B., Matson, P. A., Richardson, K., Oldfield, F., Schellnhuber, H.-J., Turner II, B. L., Wasson, R. J. and Springer, V. 2005. Global Change and the Earth System: A Planet Under Pressure. - IGBP, p. 336.
Steinfeld, H. and de Haan, C. (eds.). 1997. Livestock - Environment interactions: Issues and options. - Food and Agriculture Organization of the United Nations, United States Agency for International Development, World Bank, European Commission Directorate-General for Development - Development Policy Sustainable Development and Natural Resources; Published by Harvey Blackburn,.
Swiss Re. 2002. Opportunities and risks of climate change.
Thomas, W. L., Sauer, C. O., Bates, M. and Mumford, L. (eds.). 1956. Man's Role in Changing the Face of the Earth. - U. of Chicago Press.
Tukker, A. 2006. An Environmentally Extended Input-Output database for the EU25. International Society for Ecological Economics (ISEE) 9th Biennial Conference on Ecological Sustainability and Human Well-Being.
Turner, B. L., Clark, W. M., Kates, R., Richards, J. F., Mathews, J. T. and Beyer, W. B. (eds.). 1990. The Earth Transformed by Human Action: Global and Regional Changes in the Biosphere Over the Past 300 Years. - Cambridge University Press.

Turner, K. R., Lenzen, M., Wiedmann, T. and Barrett, J. In press. Examining the global environmental impact of regional consumption activites – Part 1: A technical note on combining input-output and ecological footprint analysis. - Ecological Economics.
UNECE/FAO. 2005. European Forest Sector Outlook Study (EFSOS). - United Nations Food and Agriculture Organization.
UNEP. 2002. Global Environmental Outlook 3. - EarthPrint.
UNSD. 2007. UN Commodity Trade Statistics Database (COMTRADE). - UNDESA – United Nations Department of Economic and Social Affairs – Statistics Division.
van den Bergh, J. and Verbruggen, H. 1999. Spatial sustainability, trade and indicators: an evaluation of the 'ecological footprint. - Ecological Economics 29.
van der Voet, E., Oers, L. v. and Nikolic, I. 2004. DematerializationNot Just a Matter of Weight. pp. 121-137.
van Vuuren, D., Smeets, E. and de Kruijf, H. 1999. The ecological footprint of Benin, Bhutan, Costa Rica and the Netherlands. - RIVM, p. 64.
Vitousek, P. M., Ehrlich, P. R., Ehrlich, A. H. and Mateson, P. A. 1986. Human appropriation of the products of photosynthesis. - BioScience 34: 368-373.
Vitousek, P. M., Mooney, H. A., Lubchenko, J. and Melilo, J. A. 1997. Human Domination of Earth's Ecosystems. - Science 277: 494-499.
von Weizsäcker, E. U., Lovins, A. and Lovins, H. 1995. The factor four. - Earthscan.
Wackernagel, M., Hamilton, K., Loh, J. and Sayre, J. 2002. Accounting for Sustainable Development: Complementary Monetary and Biophysical Approaches. Prepared for the OECD Roundtable on Sustainable Development, June 15, 2002. - Redefining Progress and Environment Department of World Bank.
Wackernagel, M., Lewan, L. and Hansson, C. B. 1999. Evaluating the Sustainability of a Catchment Area: The Ecological Footprint concept applied to Malmöhus County and the Kävlinge Watershed. Southern Sweden. - (Submitted).
Wackernagel, M., Monfreda, C., Moran, D., Wermer, P., Goldfinger, S., Deumling, D. and Murray, M. 2005. National Footprint and Biocapacity Accounts 2005: The underlying calculation method. - Global Footprint Network.
Wackernagel, M., Monfreda, C., Schulz, N. B., Erb, K.-H., Haberl, H. and Krausmann, F. 2004. Calculating national and global Ecological Footprint time series: resolving conceptual challenges. - Land Use Policy 21: 271–278.
Wackernagel, M. and Rees, W. 1996. Our Ecological Footprint: Reducing Human Impact on the Earth. - New Society Publishers.
Wackernagel, M. and Richardson, D. 1998. How to calculate a Household's Ecological Footprint. - Anáhuac University of Xalapa and University of Texas.
Wackernagel, M., White, K. S. and Moran, D. 2004. Using Ecological Footprint accounts: from analysis to applications. - International Journal of Environment and Sustainable Development 3: 293-315.
Wallerstein, I. 1974. The Modern World System: Capitalist Agriculture and the Origins of the European World Economy in the Sixteenth Century. - Academic Press.
Weidmann, T., Lenzen, M., Turner, K. R., Minx, J. and Barrett, J. 2007. Multiregional Input-Output Modelling Opens New Opportunities for the Estimation of Ecological Footprints Embedded in International Trade. International Ecological Footprint Conference (Stepping up the Pace: New Developments in Ecological Footprint Methodology, Policy & Practice).
Weidmann, T., Minx, J., Barrett, J. and Wackernagel, M. 2006. Allocating Ecological Footprints to Final Consumption Categories with Input-Output Analysis. - Ecological Economics 56: 28-48.
Weisz, H. 2007. Combining Social Metabolism and Input-Output Analyses to Accouunt for Ecologically Unequal Trade. - In: Hornborg, A., McNeil, J. R. and Martinez-Alier, J. (eds.), Rethinking Environmental History: World System History and Global Environmental Change. AltaMira Press, pp. 289-306.
Weisz, H. and Duchin, F. 2006. Physical and monetary input–output analysis: What makes the difference? - Ecological Economics 57: 534-541.
Weterings, R. and Opschoor, J. B. 1994. Environmental Utilisation Space and Reference. Values for Performance Evaluation. - Milieu 9: 221-228.
World Resources Institute. 1997. Resource Flows: The Material Basis of Industrial Economies. - In: Wuppertal Institute, Netherlands Ministry of Housing and National Institute for Environmental Studies (eds.). - World Resources Institute.
World Resources Institute. 2007. State of the World 2007: Our Urban Future. - World Resources Institute.
WWF. 2006. Living Planet Report 2006. - In: Loh, J. (ed.). - WWF International.
WWF European Policy Office. 2005. Europe 2005: The Ecological Footprint. - WWF International.