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Trading spaces: Calculating embodied Ecological Footprints in international trade using a Product Land Use Matrix (PLUM)

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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. The results show that the largest interregional flows are from Latin to North America, and from North America to Asia-Pacific. Grouping countries by GDP, high and middle income countries appear in Footprint terms to trade predominantly with other high and middle income countries and much less with low income countries.

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 (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. Natural resource accounting develops tools that measure the ecological, as opposed to the financial, balance of trade. The specific question which this study attempts to answer is this: How large of an Ecological Footprint ("Footprint") does a given

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country exert inside the borders of each of its trading partners?[1] This paper describes a method for calculating the embodied Ecological Footprint in trade flows. The UN COMTRADE international trade database is multiplied with a matrix of per-product Footprint yield coefficients (t/ha). This matrix, which we refer to as a Production Land Use Matrix or PLUM, is derived from Global Footprint Network's National Footprint and Biocapacity Accounts. (Global Footprint Network, 2005; UNSD, 2005). The result is the complete COMTRADE bilateral trade database translated into units of Footprint hectares.

1.2. *Related studies*

This study represents the first global, bi-lateral assessment of international trade using the Ecological Footprint. Wiedmann et al. (2007) and Turner and et al. (2007) 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 (1936, 1970). Early economic global I–O models were developed in the 1980s and 1990s, e.g. (Duchin and Lange, 1994; Leontief and Duchin, 1986). Limits of data availability and computability have been ever present challenges. The MOSUS project (Lutz et al., 2005) is extending the GINFORS global econometric model with environmental load indicators, and the EU EXIOPOL project is building environmentally extended I–O tables again. These models tend to be econometric in nature, or, if environmental, tend to track finely specified impacts. The work presented in this study uses a high level environmental load indicator to measure gross international environmental burden shifting.

An 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 Wiedmann 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 4.3.1 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; Weidmann et al., 2006) 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. Peters (2007) has studied the suitability of the GTAP database for use in a global multi-region I–O (MRIO) study.

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 substances through economies and supply chains (c.f. Graedel and Allenby, 1995; Peters and Hertwich, in press; Weber and Matthews, 2007). 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., in press; Munksgaard and Pedersen, 2000; Weber and Matthews, 2007; Wiedmann et al., 2007; Wilting and Vringer, 2007). The results of Ahmad and Wyckoff are widely cited; see section 4.3.4 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. Measuring ecologically unequal exchange

The Ecological Footprint (EF) was chosen to measure the biophysical balance of trade, rather than other available measures, for several reasons. The Footprint is an integrated measure which builds on the concepts of life cycle analysis, bioproductivity accounting, and embodied energy analysis to provide a readily understood, single numerical indicator comparable across studies. It should be noted that biophysical accounting does not demand finding a perfect unit which can measure the ecological value of natural goods and services. A

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[1] Nations also exert ecological impacts 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.

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.

Material flow analysis (Fischer-Kowalski, 1998; Haberl et al., 2004a,b; Schmidt-Bleek, 1994; World Resources Institute, 1997) measures resource flows in units of weight. A significant 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 (van der Voet et al., 2004). EF accounts are built on MFA but extend the concept by offering additional information regarding the biophysical intensity of material 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). Mineral products (ores, minerals, and fossil fuels) certainly have ecological impacts in their extraction and use, but the extent of their environmental impact is likely not directly proportional to their physical weight.

Energy-based metrics such as ‘eMergy’ (embodied energy or energy memory) (Costanza, 1980; Odum, 1971) 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. 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.

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 usefulness to man (its suitability for agriculture), not its simple carbon accumulation potential. (Haberl et al., 2004b).

For this study we chose to use the Ecological Footprint (Monfreda et al., 2004; Rees, 1992; Wackernagel et al., 2005; Wackernagel and Rees, 1996) to assess the ecological value of international trade. The EF measures how much of the regenerative capacity of the biosphere is appropriated by human activities. 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 in global hectares (gha), which is land with world-average bioproductivity. In this study we report results in units of actual hectares (ha), rather than global hectares, in order to simplify the analytical task as well as facilitate mapmaking. Future work will use global hectares. The Footprint indicator is designed to underestimate human impact wherever there is methodological or data uncertainty. A large body of literature exists examining the strengths and shortcomings of the Ecological Footprint approach (Best et al., 2008; Chambers, 2001; Costanza, 2000; George and Dias, 2005; Neumayer, 2004; Schaefer et al., 2006; van den Bergh and Verbruggen, 1999).

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 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.) 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, stated or implied, penalizing trade.

3. Description of methodology

The method for calculating the ecological weight of trade flows consists of combining national level Footprint accounts with the United Nations Statistics Department’s COMTRADE global trade database (UNSD, 2007). Each of the products[2] in the 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 traditional global hectares in order to facilitate mapmaking.[3]

The National Footprint Accounts provide a robust, detailed accounting of the net 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 Footprint Accounts also calculate, for each nation, the Footprint area it uses 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).

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

[3] Global hectares (gha) are the typical units used to express Footprint results. A global hectare is one hectare of land with world-average bioproductivity. Hectares may be converted into global hectares by using the equivalence and yield factors published in the National Footprint Accounts. Global hectares facilitate comparison between Footprint studies, however their use complicates mapmaking as highly productive countries may be able to export more global hectares worth of agricultural products than they have actual hectares under cultivation.

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	Live poultry	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

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), expressing how many hectares of each of the four major land use types (pasture, cropland, forest, and ocean/marine) are occupied for the production of 1 t of that product.[4] Built-up land was assumed to not be 'traded' and was excluded from the analysis. Built up land represents less than 10% of land use worldwide, and likely <2% of 'traded' Footprint land, so its inclusion would be nearly invisible in the resulting maps; furthermore most of the environmental impacts of urban land use can be reasonably proxied with the Energy Footprint, which is included. Table 1 shows some representative entries from the PLUM.

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

Ideally one output of the National Footprint Accounts would be a list of per-product Footprint intensities. These data would directly comprise the PLUM. However, the National Footprint Accounts 2006 Edition (the most current version at time of writing) offers these yield factor data in a different product nomenclature (SITC rev. 3) than that used by COMTRADE (HS02).[5] 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 Footprint Accounts but tagged products by HS02 code rather than SITC code. The SITC and HS nomenclatures overlap but do not correspond entirely so manual product correspondence was required. 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 multiplied by Footprint yield coefficients. This results in a full bilateral trade dataset reporting the number of hectares traded between countries. The National Footprint 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 and apply the production yields to exports.

The COMTRADE dataset does not report weight values for 13% of records, representing 26% of total trade value (in USD). Since all the Footprint yield coefficients are in units of weight, this study used price estimates ($/t) to estimate missing weight values. The commodity prices were calculated as follows. 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 50 kg 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). These countries were chosen as a representative sample of major players in global trade, and countries for whom data would most likely be reliable. 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 Footprint 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/year. The second yield

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[4] The National Footprint 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.

[5] SITC, or Standard International Trade Classification, was used from c. 1960 to 1990, and was superseded by the Harmonized System (HS) in 1992.

set is based on the IPCC recommended methodology for estimating national forest growth (IPCC, 2006). The authors 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 'observed yield' by dividing the annual FAO-reported timber production (m^3) by the FAO-reported forest area (ha). The 'observed 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 observed 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 observed yield 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 observed 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 1 t of each HS02 product. Countries with missing yield data (a majority of countries, but collectively responsible for <20% of global timber harvest) were assumed to have world-average timber yield. Three validation filters were applied to the yield coefficient 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 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 Footprint Accounts. The yields for three product codes of high-quality fish ready for human consumption[6] 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 147 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), this study uses 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. The 79 HS02 categories with no directly matching FAOSTAT category were assigned averages of similar products. (In most of these cases similar products were easy to identify.) 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. 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. FAOSTAT coverage is comprehensive but in the few cases where countries had incomplete yield data, missing entries were filled in with world average yields.

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 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., 2007a,b; 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.

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[6] 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).

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 Footprint Accounts. For this study, estimates of pasture product yields were derived from the existing National Footprint Accounts. The authors believe 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.[7]

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 the nation providing the goods.[8] 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. Knowing one country's Energy Footprint in another country is useful in designing carbon abatement strategies, and this information is reported in parallel in this study. In the results tables in this paper tables reporting hectares (ha) omit the energy Footprint, and tables reporting global hectares (gha) include the energy Footprint.

This study built a single sector I–O model to estimate each nation's import and export of CO_2. A single sector I–O model represents each country as having a single economic sector; for other examples see (Lenzen et al., 2007a,b; Proops et al., 1999). CO_2 imports and exports were assumed to hold the same ratio to domestic emissions as imports and exports in monetary value do to GDP. Within this national total CO_2 import and export, the CO_2 burden was allocated to different products using embodied energy estimates. We made the simplifying assumption 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)[9] for each HS-02 product were gathered. The primary source for these figures was the embodied energy estimates in the National Footprint Accounts. These data are maintained in an in-house library at GFN based on LCA-based data from the Centre for Energy and Environmental Studies (IVEM) at University of Groningen and augmented with data from other sources by Stockholm Environment Institute–York (Barrett and Wiedmann, 2005). These data were translated from SITC to HS02 nomenclature in a similar manner as described for other products above. 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, which were then scaled to match the gross CO_2 import and export figures estimate from the single sector IO model.

Estimating embodied energy and carbon in products remains a difficult exercise. Estimating total embodied CO_2 in trade using embodied energy estimates alone yields obviously implausible results: our initial findings using this method alone showed Australia exporting more CO_2 than it emits. The problem is that the LCA studies used to generate the embodied energy data have overlapping boundaries, so they cannot be directly summed. The results of our revised single sector IO model agree well with those of a similar study by Ahmad and Wyckoff (see section 4.3.4). (Weidmann et al., 2007; esp. Table 1) present 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 errors in the calculation of coefficients can lead to the sum of the Export Footprint from the resulting dataset not equalling the Export Footprint as calculated in the National Footprint Accounts. This is a problem because if embodied Footprints are calculated for individual products it could result in double counting of Footprint area (e.g. if a country exports both bread and wheat, care must be taken not to double count the Footprint area of the country's wheat production twice for each product.) Conceptually if the complete PLUM is generated from National Footprint Accounts or other complete accounting (such as a physical I–O table, or PIOT) this risk is avoided, but given that the Accounts are generated primarily from raw resource accounts and the PLUM entries generally represent more processed child products, this is difficult to ensure. An I–O approach guarantees that no sector of the studied economies is omitted (Weidman and Lenzen 2007). An I–O approach is

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[7] 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).

[8] 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.

[9] 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.

Table 2 – Global total Footprint, value, embodied CO_2, and weight, by HS02 section.

	Value (bil. USD)		Footprint (M ha)		CO_2 (Mt)		Weight (Mt)	
HS02 section	Export	Import	Export	Import	Export	Import	Export	Import
Sec. I– animals & products	$126	$133	260	268	81	73	68	71
Sec. II– vegetable products	$139	$150	141	148	134	101	462	459
Sec. III– organic fats and oils	$23	$24	–	–	42	34	45	45
Sec. IV– prepared food	$191	$199	50	36	438	166	1,069	311
Sec. IX– wood & fiber products	$629	$673	–	–	746	730	5,436	5,347
Sec. V– mineral products	$540	$586	–	–	503	485	420	515
Sec. VI– chemicals	$257	$268	20	23	298	296	184	458
Sec. VII– plastics & rubber	$53	$54	–	–	5	9	7	10
Sec. VIII– hides & leather	$72	$75	43	39	105	94	402	282
Sec. X– wood pulp & paper	$146	$151	27	39	184	160	194	308
Sec. XI– textiles	$378	$380	17	19	254	292	67	91
Sec. XII– misc. dress accessories	$57	$64	–	–	6	10	5	5
Sec. XIII– stone, ceramic, etc.	$71	$72	–	–	52	50	104	109
Sec. XIV– pearls and jewels	$117	$121	–	–	1	2	0	1
Sec. XIX– armaments	$390	$401	–	–	848	863	562	926
Sec. XV– base metals	$1,826	$1,843	–	–	497	801	197	827
Sec. XVI– machinery	$792	$768	–	–	343	278	144	158
Sec. XVII– vehicles	$218	$225	0	0	29	100	16	123
Sec. XVIII– precision instruments	$6	$5	–	–	1	0	0	0
Sec. XX– misc. mfg. articles	$145	$164	12	10	67	90	58	59
Sec. XXI– art & antiques	$169	$166	–	–	–	–	–	–
Total	$6,345	$6,518	570	581	4,634	4,633	9,442	10,105

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. I–O tables allow analysis of the transformation efficiencies of various countries. This COMTRADE based analysis is restricted to analyzing the endpoints of trade flows and is not suited to analyzing product transformation along a multi-country production chain. 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 Footprint 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., submitted for publication; 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).

One key limitation constraining the accuracy of this study's implementation was that the PLUM should be filled using the National Footprint Accounts. Since the Accounts were not

Table 3 – Imports of Ecological Footprint between regions.

Footprint imports (M ha), by geographic region

Source:

Destination:	Africa	Asia-Pacific	Latin America	M. East & C. Asia	North America	Other Europe	Western Europe	From all countries
Africa	3.0	2.3	0.1	5.1	0.9	0.5	11.7	23.5
Asia-Pacific	5.7	63.0	6.3	12.8	22.4	1.1	11.5	122.9
Latin America	3.9	9.1	14.1	5.6	16.3	1.0	14.4	64.4
M. East & C. Asia	6.6	3.5	0.2	13.8	0.5	1.9	7.9	34.4
North America	5.8	41.1	61.9	5.1	57.2	0.4	7.3	178.9
Other Europe	1.1	0.6	0.1	9.8	1.0	11.3	20.4	44.2
Western Europe	3.3	5.7	1.1	7.5	2.3	4.5	60.7	85.1
To all countries:	29.4	125.2	83.7	59.8	100.6	20.8	133.9	

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 likely less accurate than would be if produced by the National Footprint Accounts. This deficiency can be overcome by repeating the study when an HS02-coded edition of the Accounts is available. Producing an HS02-coded National Footprint Accounts is itself an extremely 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. Determining conversion factors to move between raw materials and highly manufactured products is a difficult challenge; and was a serious challenge in this study (for more on this see Weidman and Lenzen, 2007).

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 Supplementary Material for a list of the nations which reported.

A future direction of study using the PLUM could be to produce a timeseries. Data in the National Footprint 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 time series would be a worthwhile, though challenging, effort.

4. Results & discussion

4.1. *Discussion of key findings*

The primary intention of this paper has been to introduce the PLUM methodology. The full dataset of results will require further work to analyze. This section offers a first order summary of the results. The summary tables in this section separate the energy Footprint and the land-area Footprint. Because the Energy Footprint is separated out, the virtual 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.

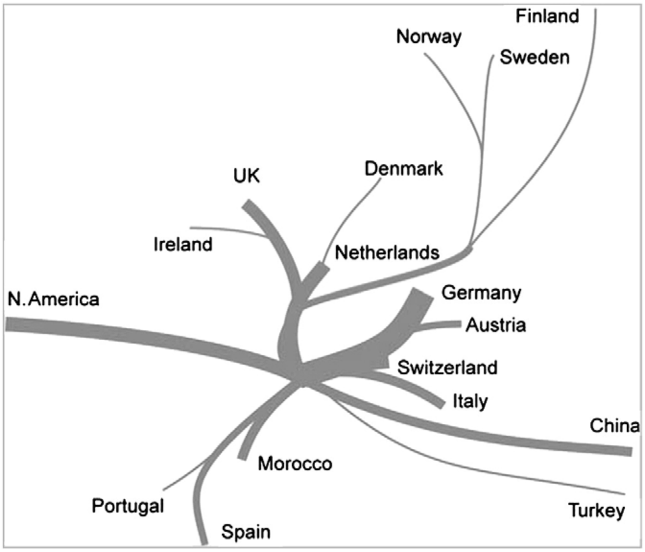

Fig. 1 – Top sources for French Footprint imports.

Table 2 sums our results globally, categorized by top-level HS02 categories. The results observed are expected. In total, 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 is small in comparison to biological resources. Weighting by CO_2 generally agrees with the monetary value; that is, trade volumes measured in units of monetary value and embodied CO_2 content have approximately a 1:1 ratio.

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

Table 3 summarizes the direct non-energy Footprint flows between regions.[10] Three of the four largest trade volumes are intraregional. 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 less than half as much Footprint as does North America (85.1 Mha vs. 178.9 Mha), though this could be caused by the enormous trade between US and Canada. North America is, unsurprisingly, a net importer of Footprint, importing 178.9 Mha (of which 57.2 Mha comes from intraregional trade and the remaining 121 Mha is from outside the region) and

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[10] 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.

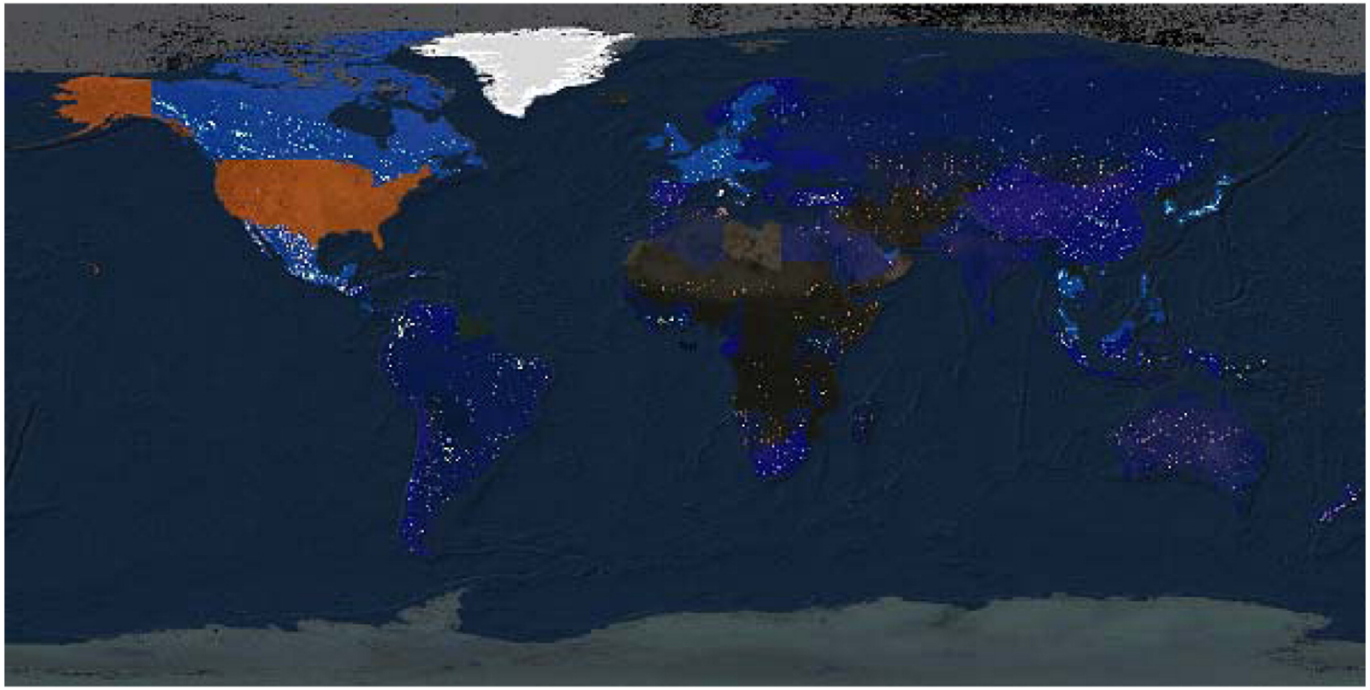

Fig. 2 – USA's Ecological Footprint around the world. Lit speckles represent areas within the countries from which the US imports biological capacity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4 – Example for Finnish Footprint trade: Andersson's vs. this study's findings.

Andersson & Nevalainen (2003)				This study			
	Export	Import	Net export		Export	Import	Net export
World	35,428	32,539	2,890	World	30,576	22,746	7,830
OECD	26,730	16,871	9,859	OECD countries	25,751	12,396	13,355
				Western Europe	21,413	9,746	11,667
				Other Europe	2,019	2,935	−916
Rest of Europe	2,559	12,190	−9,630	*Europe*	23,432	12,681	10,751
				Low income	194	199	−5
				Middle income	5,609	11,380	−5,771
Developing countries	5,283	1,342	3,914	*Developing countries*	5,803	11,579	−5,776
				EU–15 countries	20,470	9,678	10,792
EU	13,916	10,972	2,945	All EU countries	22,711	12,495	10,216
North America	2,128	542	1586	North America	2,146	608.05	1537.63
North Africa	995	13	983				
Rest of Africa	163	100	64				
Africa	1,158	113	1,047	Africa	456	174	281
Oceania	251	105	146				
Rest of Asia	4,323	1,307	3,015				
Asia-Pacific	4,574	1,412	3,161	Asia-Pacific	1,739	2,334	−595
Middle East	669	9	660	M. East & C. Asia	2,434	6,194	−3,760
South America	283	131	152	Latin America	370	754	−384
Units: 1000 gha							

Categories in italics are sums inserted to facilitate comparison.

exporting outside the region 100.6−57.2=43.4 Mha (approximately the area of California). The results for Africa are also notable, showing the continent being only a slight exporter (with 23 Mha imported and 29 Mha exported).

4.2. *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 map styles may be used to visualize the international trade in terms of embodied Footprint. Fig. 1 illustrates 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 Fig. 2) is a 'nighttime lights'-type map which shows, for a given country, the areas around the world where that country's Footprint falls.

4.2.1. *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.

4.2.2. *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 (Fig. 2) (Heumann and Moran, 2006). This technique combines national Footprint data with global remote sensing data. Though it is not possible to determine the exact location of production of specific imports, the area used in other countries to produce imports can be attributed to a land-use type within each partner country. Footprints attributed to forest, pasture, and cropland are represented by lit pixels tinted green, brown, and yellow, respectively. Land-use types are determined using the Global Land Cover Classification (Hansen et al., 1998). The lit pixels showing 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). Lit pixels are scattered within countries according to land use and NPP; not according to sub-national production statistics.

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 light blue cloropleth fill layer to indicate the amount of embodied CO_2 imported from each trading partner.

4.3. *Comparison with other studies*

4.3.1. *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 4 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

Table 5 – 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)

coefficients are based on earlier versions of the National Footprint Accounts spreadsheets.[11] 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.

4.3.2. *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 Footprint 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.[12]

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,[13] and adjusted for trade, 12.9 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.

4.3.3. *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." Table 5 shows our results for these four countries. With the exception of Vietnam (which our results show to be a net exporter, not net importer) our MFA findings agree with Weisz. However, using Footprint instead of MFA, we observe a different result: in Footprint terms three of the four countries are net *exporters*, not importers. This observation underscores the fact that MFA and Footprint analyses can have strikingly different conclusions, as the two tools measure flows differently.

4.3.4. *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. Fig. 3 compares our results with those from Ahmad and Wyckoff. For 15 of the 24 compared countries the results are similar, and of the 9 which disagree only 2 (New Zealand and Hungary) disagree by more than a factor of 3.

5. Conclusion

Countries' Ecological Footprints fall across the globe. 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 presented here is a natural complement to individual product trace studies, setting context and enabling stronger general conclusions to be drawn.

As globalization accelerates, many nations depend on natural resources and ecological services from abroad. 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. Knowing the patterns and extent of their ecological trade relationships will help countries understand more clearly

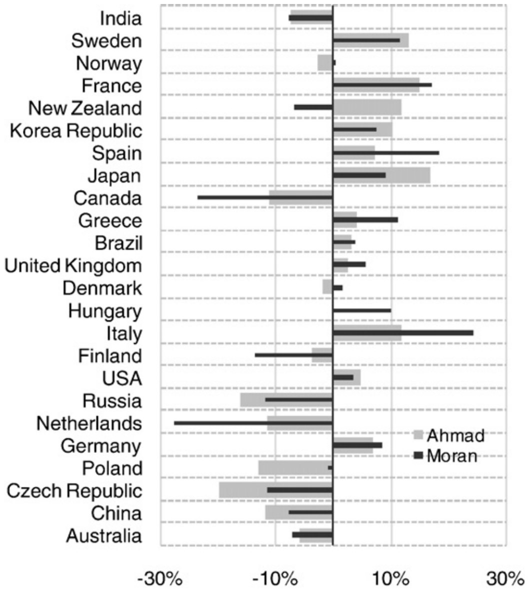

Fig. 3 – Net CO_2 imports as percentage of domestic emissions – Moran vs. Ahmad and Wyckoff.

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[11] 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.

[12] The van Vuuren study omitted marine product imports, which our results indicate are negligible for the Netherlands at <0.01 ha/cap.

[13] 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.

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. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolecon.2008.11.011.

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