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Analysis

Does Ecologically Unequal Exchange Occur?

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ABSTRACT

The hypothesis of ecologically unequal exchange posits that low and middle income developing nations maintain an ecological deficit with wealthy developed nations, exporting natural resources and high impact commodities thereby allowing wealthy economies to avoid operating ecologically impactful industries at home. In this survey we assess the footprint of consumption of 187 countries using eight indicators of environmental pressure in order to determine whether or not this phenomenon occurs. We use input–output analysis with a new high resolution global Multi-Region Input–Output table to calculate each trading pair's balance of trade in biophysical terms of: GHG emissions, embodied water, and scarcity-weighted water content, air pollution, threatened species, Human Appropriated Net Primary Productivity, total material flow, and ecological footprint. We test three hypotheses that should be true if ecologically unequal exchange occurs. One: The inter-regional balance of trade in biophysical terms is disproportional to the balance of trade in financial terms. We find this is true, though not strongly so. Two: Exports from developing nations are more ecologically intensive than those from developed nations. We find this is true. Three: High-income nations disproportionately exert ecological impacts in lower income nations. We find this is false: high income nations are mostly exporters, not importers, of biophysical resources.

1. Introduction

Countries seek to maximize their welfare while minimizing the environmental cost of that welfare by decoupling economic growth from physical throughput. Undermining these efforts to improve resource efficiency are complex and opaque international supply chains through which the footprint of wealthy countries may be displaced into poorer countries where environmental protections may be less or sensitivity greater. In the context of CO_2-intensive production moving offshore, this phenomenon is called carbon leakage. In the broader context of natural resources being extracted from resource-rich but cash-poor countries to satisfy consumer demand in wealthy countries, it is called ecologically unequal exchange (Emmanuel, 1972; Hornborg et al., 2007; Martinez-Alier, 2007; Muradian and Giljum, 2007; Muradian et al., 2002; Røpke, 2001; Wallerstein, 1974).

In this study we simply ask whether or not ecologically unequal exchange does occur, not whether or not it ought to. In classical economic thought ecologically unequal exchange is a desirable, or natural, outcome since it is a result of specialization and trade. Countries abundant in natural resources should have more resource-intensive exports. However critics (e.g. Daly and Townsend, 1993; Norgaard, 1990; Rees and Wackernagel, 1999) reply that, due to a variety of market failures, natural resources and ecosystem services are often substantially under-valued and thus not allocated efficiently or equitably. It is predominantly pollution sinks, in air and water, and universally important resources, such as tropical rainforests, that are discussed as natural resources poorly allocated with their current prices (often zero).

We propose three testable hypotheses that should be true if ecologically unequal exchange is occurring:

1. The inter-regional trade balances in physical terms are not uniformly proportional to the financial balances of trade.
2. Exports from low-income nations are more ecologically intensive, that is, they contain more embodied environmental impact per dollar sold, than exports from high-income nations. Phrased in the inverse, low-income countries sell their natural resources more cheaply.
3. High-income nations exert a disproportionately large fraction of their ecological impacts in low income nations.

In this study we test these hypotheses empirically using a new high-resolution global multi-region input–output table. We have calculated the balance of trade between each of 187 counties in terms of eight indicators of environmental pressure: GHG emissions, air pollution, water and scarce water use, threatened species, Human Appropriated Net Primary Productivity, material use, and ecological footprint. These eight indicators together provide a broad measure of ecological pressure.[1]

[1] The air pollution and species loss indicators are measures of impacts; the other indicators are measures of pressure. All the indicators strive to measure the actual, or risk of, impact. Below we generally employ the term impact even though this is not always strictly accurate as some indicators merely measure pressure not impact.

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2. Methods and Data

We tested the aforementioned three hypotheses by calculating the footprint[2] of eight biophysical indicators using Leontief's environmentally extended multi-region input–output (MRIO) analysis (Forssell and Polenske, 1998; Leontief, 1966; Leontief and Strout, 1963; Peters, 2008). Leontief's demand-pull method is most often used to determine the economy-wide (monetary or physical) repercussions of changes in final demand. It has also been used in various approaches to calculating balances of trade between the country suffering the impact (the producer) and the country whose consumers ultimately drive that consumption (Kanemoto et al., 2012; Serrano and Dietzenbacher, 2010). All impacts of production, intermediate processing, and transportation are attributed to final consumers,[3] in whichever country they reside. While much environmental impact occurs purely domestically, the acceleration of globalization means that more than ever consumers are driving environmental impact far beyond their own country's borders.

Leontief's approach is a standard technique for calculating each consumer's full footprint. Using the Eora MRIO (Lenzen et al., 2012a) table containing $n = 187$ countries each with between 26 and 501 sectors, for a total of $s = 15{,}909$ sectors, and evaluating $p = 8$ biophysical (or "satellite") indicator inputs,[4] the traditional per-country consumption footprint $\mathbf{F}$ $(p \times n)$ resulting from monetary expenditure y $(e \times n)$ of final consumers is $\mathbf{F} = \mathbf{Q}\hat{\mathbf{x}}^{-1}\left(\mathbf{I}-\mathbf{T}\hat{\mathbf{x}}^{-1}\right)^{-1}\mathbf{y}$, where $\mathbf{x}$ $(s \times 1)$ denotes per-sector gross output, the ^ operator denotes diagonalization, $\mathbf{T}$ denotes the $s \times s$ MRIO table and $\mathbf{I}$ an $s \times s$ identity matrix. $\mathbf{Q}$ $(p \times s)$ contains the per-sector direct impacts (t CO_2 emitted, Gl water used, etc.) and the term $\mathbf{Q}\hat{\mathbf{x}}^{-1}$ (hereafter $\mathbf{q}$) represents each sector's indicator intensity (direct impact per \$1 of production). The eight indicators of ecological impact were attributed to production activities in each country. Details on the procedure differed by indicator, and are discussed below. The Leontief inverse was then applied in order to reattribute these impacts from country of production to the country in which the implicated products are finally consumed.

MRIO analysis of the world economy captures the entire international trade network; this means that when the resource requirements for final demand of a country D are appraised, MRIO analysis links D's final demand not only with its own domestic resource inputs, but also with the resource inputs in origins of D's imports. For example, if D imports products from C, and these were made using imports from B into C, and from A into B into C, then MRIO includes into D's footprint those resources used in A, B and C, ultimately serving to satisfy D's final demand.

The high sector detail of the Eora MRIO is important as it allows for better product differentiation thus mitigating error arising from sectoral aggregation. Consider aluminum production. If aluminum products are included in a broad 'nonferrous metals' sector the MRIO analysis will not be able to distinguish between embodied CO_2 in aluminum products, which are especially CO_2 intensive, and other nonferrous metal products, such as steel or copper which have a much lower CO_2 intensity (Allwood and Cullen, 2012). Distinguishing a separate 'aluminum' sector would provide a more accurate account of the embodied CO_2 in trade. While more disaggregation is conceptually always preferable, there are decreasing marginal returns to added detail. Su et al. (2010) found that diminishing returns sets in at ≈40 sectors, though Zhou et al. (2012) found that further disaggregation does improve accuracy. The Eora MRIO project explicitly aimed to preserve the full detail provided by national statistical bureaux and is the most detailed MRIO yet built.

The footprints of consumption calculated using the Eora MRIO database agree well with previously published results. As seen in Fig. 1 (reproduced from data in Lenzen et al., 2012a) there is good agreement between the final consumption footprint as calculated by Eora and other research groups. The figure compares Eora's results for the national footprint of final consumption for CO_2, ecological footprint, and embodied water with calculations of these same figures by Peters et al. (2011) (using GTAP 7; see Narayanan and Walmsley, 2008), Global Footprint Network (2010) and the Water Footprint Network (Mekonnen and Hoekstra, 2011). We see a small number of outliers in terms of ecological footprint, and a slight bias toward smaller water footprints in Eora, but overall substantial agreement.

2.1. Data Sources

For each indicator, the input data consist of a vector with the measure of the impacts associated with total production for each sector/product. Indicator datasets vary by level of detail; for example CO_2 emission inventories are accurate across all sectors of an economy while the water use data are highly accurate for various individual crops but more aggregated for all industrial and commercial uses. Using these data sources as satellite indicators for the Eora MRIO is further complicated by the fact that the Eora MRIO uses different sectoral classifications for each country (depending on the level of detail provided by each country's statistical bureau). These various conversions are accomplished with the use of concordance matrices. An $n \times m$ concordance matrix contains weights that can be used to map a source vector of length n to an output vector of length m. Each concordance matrix row specifies how source vector entries should be re-allocated amongst the various sectors of the destination vector, and each row sums to 1 in order to exhaustively re-allocate the source vector entries. Further explanation of concordance matrices is available (Geschke, 2012; Lenzen et al., 2012a) and specifics

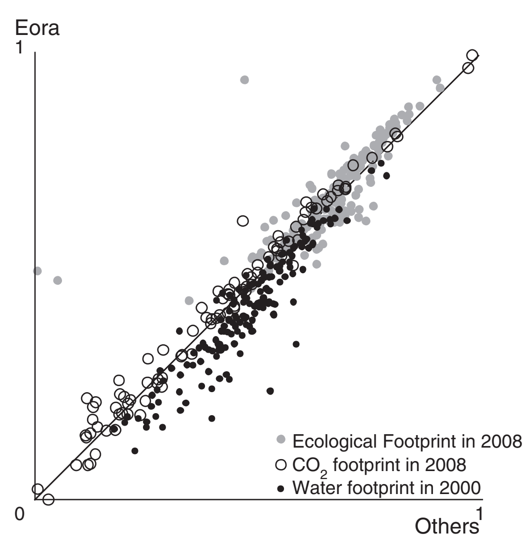

Fig. 1. Comparison of Eora per-country footprint of consumption (vertical axis) results with Ecological Footprint results from Global Footprint Network, water footprint results from the WaterStat database, and carbon footprint results based on GTAP ($y = 2008$) (horizontal axis). The vector of per-country footprints $\mathbf{f}_p$ for indicator p is first log scaled then linearly re-scaled such that $\max(\log_{10}\mathbf{f}_p) = 1$ and $\min(\log_{10}\mathbf{f}_p) = 0$ so that all three indicators can be plotted together.

[2] We use the lower case term "footprint" to refer generally to a consumption, not production, based account of environmental impact; the Ecological Footprint is one such account.

[3] In multi-region input–output analysis final consumption consists of purchases by households, government, NGOs, additions to inventories, and gross fixed capital expenditure. Note that in single-region variants of input–output analysis, exports form part of final demand, however in multi-region input–output analysis exports are endogenized into intermediate demand.

[4] Most of the eight indicators have multiple subcategories (e.g. CO_2 emissions are itemized by source type) so during calculation $p > 8$ to preserve this detail, but after the Leontief calculation $\mathbf{F}$ is aggregated back to $p = 8$ for subsequent analysis.

about the sectoral detail and construction of concordance matrices for each indicator are available within the sources cited for each.

CO_2 emissions were taken from the Eora MRIO database. Eora uses multiple sources of GHG data (primarily, EDGAR (European Commission Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL), 2009) and the UNFCCC (1997)) and provides per-sector GHG emission inventories for nearly all countries. We used national CO_2 emissions from burning of fossil fuels. The results as calculated by Eora (Kanemoto et al., 2013; Lenzen et al., 2012a) are comparable to similarly calculated carbon footprint results based on the GTAP MRIO (Davis et al., 2011; Peters et al., 2011, 2012). These data were available for all years 1990–2010.

Water footprint (WF) data were taken from the WaterStat database (Mekonnen and Hoekstra, 2010, 2011) and scarcity-weighted water data was taken from (Lenzen et al., in press). The scarcity weighting used by Lenzen et al. excludes non-scarce water by deflating water flows originating in water-abundant countries. Consistent data for water withdrawals and scarcity was only available for the year 2000. Units are in ML.

Human Appropriated Net Primary Productivity (HANPP) (Haberl et al., 2007) measures how much of each country's primary productivity (organically fixed carbon, Pg C/yr) appropriated for human use, principally by agriculture and forestry. Erb et al. (2009) calculated embodied HANPP (eHANPP) in trade flows based on direct (first-order) bilateral trade flows. We used Haberl et al.'s (2007) data on Used Extraction (biomass in crops, crop residues, grazed biomass, and wood removals, in tonnes of dry matter; also called harvested biomass), allocated that biomass to the agricultural and forestry sectors, and then calculated the biomass footprint of consumption. Data were available only for 2000.

The material footprint (raw materials, measured by weight, embodied in consumption) results are here taken from a study underway by Wiedmann and Schandl (submitted for publication) who calculated the material footprint (MF) using Eora and a global materials use database curated by CSIRO (CSIRO, 2012; UNEP and CSIRO, 2012), following similar work including Fischer-Kowalski et al. (2011), Bruckner et al. (2012), Schoer et al. (2012), and Wiebe et al. (2012). The materials database tracks 36 individual materials in four groups: biomass, ores, fossil fuel, and construction and industrial materials. Our material footprint indicator is the sum of all the materials, in tons. These data were available annually for 1990–2008. A number of studies, including Giljum and Hubacek (2001), Giljum (2004), Muradian and Giljum (2007), Weisz (2007), Singh and Eisenmenger (2011) and Singh et al. (2012) have used material flow, materials embodied in direct imports, and material intensity to evaluate ecologically unequal exchange. A survey comparing these various studies and their methods and data sources is outside the scope of this paper, but the reader should note that there is a substantial body of existing work using the material footprint to measure ecologically unequal exchange.

Biodiversity footprint results were taken from a study by Lenzen et al. (2012b). That study attributed threatened Animalia species from the IUCN Red List of Threatened and Endangered Species to the sectors directly causing those threats then used a Leontief demand-pull model to trace those threat-implicated products to final consumers. Species threats due to Mexican coffee and cocoa plantations, for example, could be attributed to coffee and cocoa consumers in the US. Plants, threats that could not be linked to specific industries (such as invasive species), and illegal activities were excluded. These exclusions mean that the domestic biodiversity footprint is under-estimated, but they do not substantially affect balance of trade as the excluded impacts are not connected to trade. The exception to this is fishing. Threats to aquatic species are attributed to the country in which the threat occurs, meaning that, for example, biodiversity impacts caused by the Chinese fishing fleets operating in Tuvaluan waters will be attributed to Tuvalu. Little data on the international movement of fleets exist, and it is difficult to quantify the impact of this attribution problem. Data on the biodiversity footprint was available for 2000. The unit is number of species threatened.

The ecological footprint (EF) measures the total area of land and sea required to produce all of the inputs and absorb all the waste of a given population (Wackernagel and Rees, 1996). The National Footprint and Biocapacity Accounts published by Global Footprint Network (2010) provide authoritative footprint data for 157 countries. However, the data and methodology used to calculate international trade in the

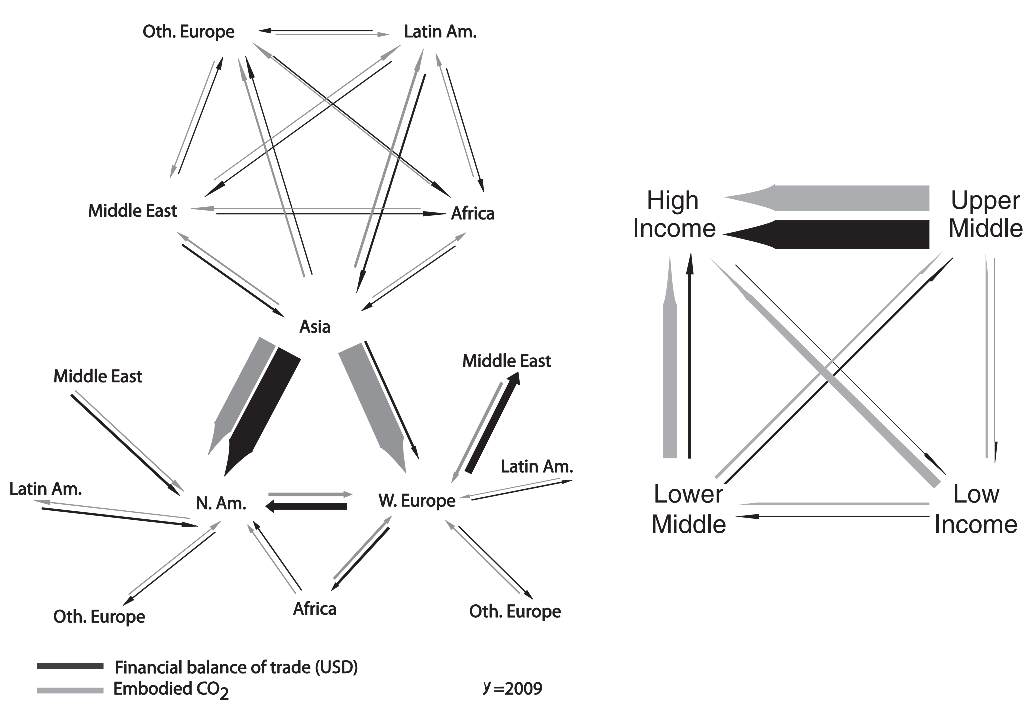

Fig. 2. Net exports in terms of embodied CO_2 and USD. Line weights are linearly scaled independently for the two variables.

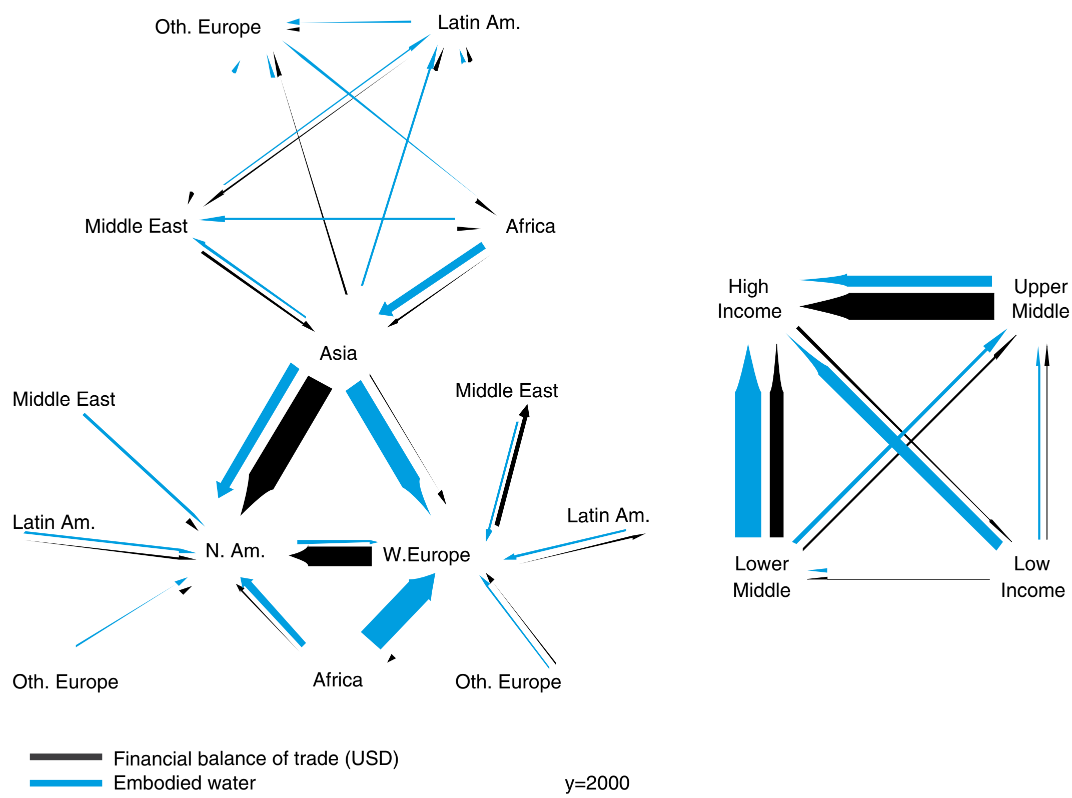

Fig. 3. Inter-regional balance of trade in terms of financial flows and in terms of embodied water. In a number of cases (e.g. Africa to W. Europe) the balance of trade in embodied water is opposite the balance of trade in financial terms.

Accounts is acknowledged to be weak (Kitzes et al., 2009; Wackernagel et al., 2005). In this study we used Global Footprint Network's calculation of the footprint of the producing nations (which provide the footprint per unit of production for various products) but used the Eora MRIO to calculate the consumption footprint. This means the footprint of consumption results may differ from those calculated by the Global Footprint Network. These data were available annually for 1990–2007 in units of globally-average hectares (gha).

Air pollution data are provided by the Eora MRIO, and were originally sourced from the EDGAR database (European Commission Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL), 2009). This dataset covers 7 air pollutants (CO, NO_x,

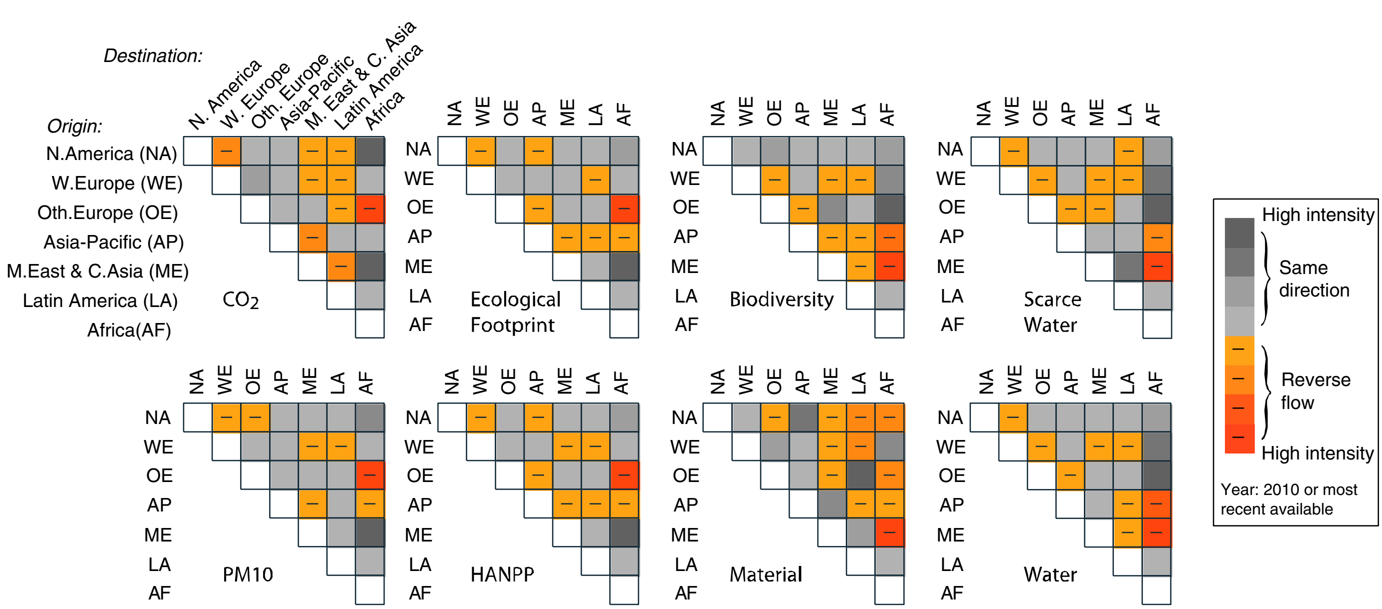

Fig. 4. Heatmap visualization of biophysical intensity of trade balance (impact per dollar, for net exports) between regions.

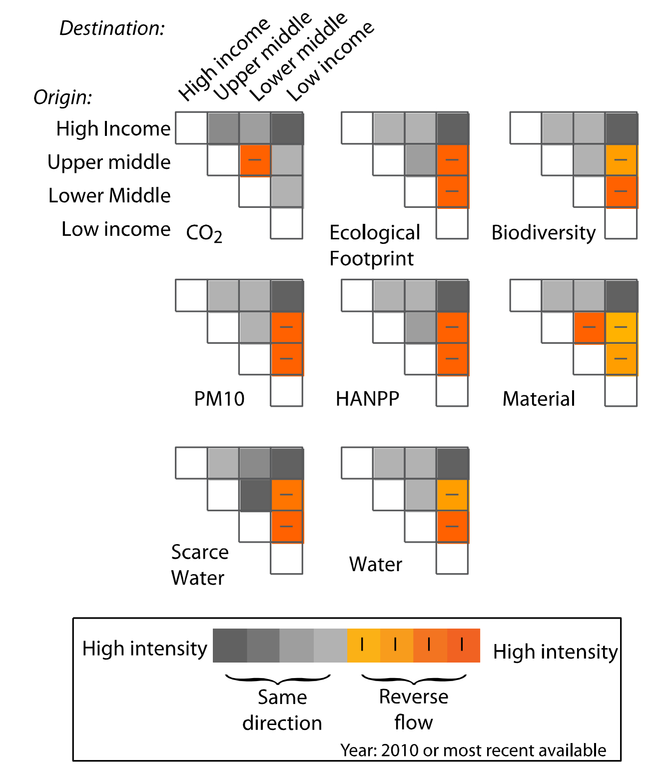

Fig. 5. Heatmap visualization of biophysical intensity of trade balance (impact per dollar, for net exports) between income groups.

SO_2, NMVOC, NH_3, HC, PM10) itemized by the sector and source of emission. We chose PM10 (airborne particulates <10 μm in size, recorded in Gg) as our air quality indicator, as it has direct impacts on human health (Medina et al., 2004). These data were available annually for 1990–2008.

3. Findings

3.1. Hypothesis 1: The Inter-regional Balance of Trade (Net Exports) in Biophysical Terms is Disproportional to the Balance of Trade in Financial Terms

This hypothesis follows from the basic ecologically unequal exchange argument that money is a poor indicator of ecological worth. We might initially expect embodied CO_2 to closely follow financial flows on the assumption that embodied energy content should create economic value. However we find that this is not always true. The left hand panel of Fig. 2 presents the inter-regional balance of trade (net exports) in terms of both financial value (current USD) and in terms of the CO_2 footprint. Region membership is defined in SI 1. (This figure, and all subsequent ones, use the most recent data year available for each indicator unless otherwise specified.) The large financial flow from Asia to North America is matched by a large carbon footprint. But despite a relatively neutral balance of trade between Asia and Western Europe there is a large imbalance in net embodied CO_2 between them. In several cases we see that the trade balance of embodied CO_2 is actually opposite that of the financial trade balance, e.g. between W. Europe and both North America and the Middle East. The financial net exports from North America to Western Europe are returned by a net export of embodied CO_2 from Western Europe to North America. Latin America is a net financial exporter to all other regions, but a net CO_2 importer from all other regions.

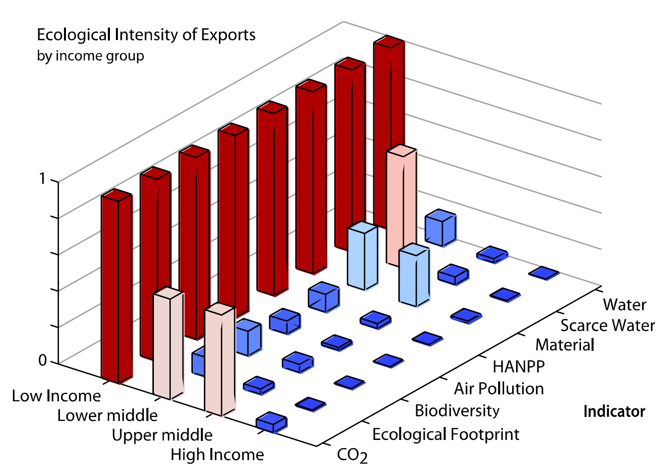

Fig. 6. Ecological intensity (impact per dollar, normalized against highest category) of exports, by income group.

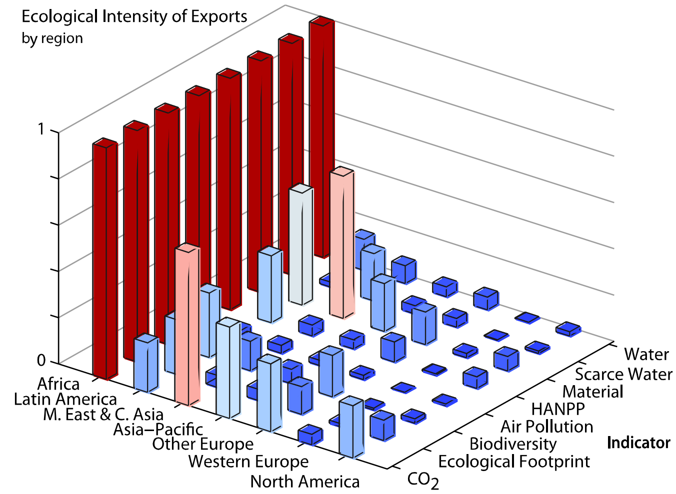

Fig. 7. Ecological intensity (impact per dollar, normalized against highest category) of exports by region.

Between income groups we see that flows of embodied CO_2 from lower middle income countries to high income countries are disproportionately larger than the financial flow. And while in financial terms high income countries are net exporters to low income countries, in terms of embodied CO_2 they are substantial net importers. This notable imbalance is in terms of the net balance of trade. Below we find that in exports from low income to high income nations are quite ecologically intensive, but in absolute terms the volume of trade is quite small. The nature of embodied environmental impacts in trade between low income and high income countries is certainly one of the most pressing questions in ecological economics, but one of the main findings of this study is that this balance of trade appears quite differently depending on how it is measured. In terms of ecological intensity, and absolute volume of trade (discussed below), this relationship between low and high income countries appears quite differently.

The interregional balance of trade in terms of embodied water flows is strikingly different from the financial balance of trade (Fig. 3). The large flow of embodied water from Asia to Western Europe is not matched in the comparatively small financial flow. In many cases the balance of trade is opposite, sometimes substantially. The small financial flow from Western Europe to Africa is returned by a large amount of water embodied in products. The effect of the water scarcity weighting is difficult to see at this level of aggregation (Fig. 11, supplementary data) though when comparing the results between unweighted and scarcity-weighted water flows we do notice

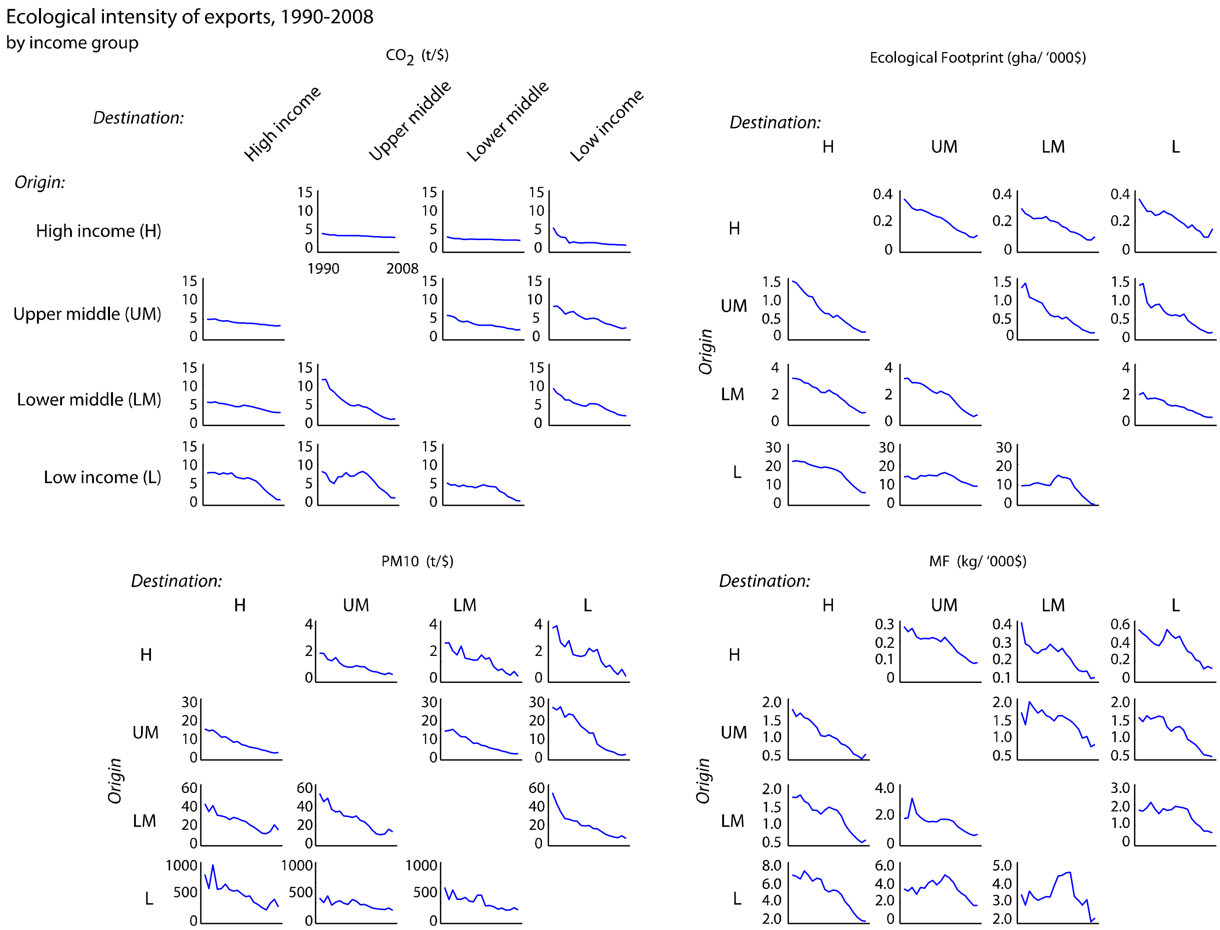

Fig. 8. The ecological intensity of exports (impact per inflation-adjusted real dollar) has improved for all inter-regional trade flows since 1990, though there remain large variations in intensity (e.g. compare PM10/$ exports from High and Low income nations).

that with scarcity weighting, Asia is not a water exporter, but a net importer of scarce water.

The full series of inter-regional trade balance figures for all eight indicators is provided in SI 2. We note several interesting findings:

- Africa exports substantial embodied water and HANPP to Western Europe and Asia, far in excess of its financial balance of trade.
- Net exports from Asia to Western Europe are modest in financial terms but contain a large flow of embodied waster, CO_2 and HANPP
- Large flows of biodiversity-threat-implicated products from Africa, Asia, and Latin America come into North America and Western Europe.

The inter-regional trade balance figures can be summarized with a heatmap (Figs. 4 and 5). In this visualization the biophysical intensity of net exports (net exports in biophysical units divided by net exports in dollars) is calculated for each pair of regions and plotted in a heatmap matrix. In order to compare multiple indicators with different units we normalize the ecological intensity i (e.g. t CO_2/$, gha/$) of each indicator to the normalized intensity $i' = \frac{i_{\text{indic}}}{\max(i_{\text{indic}})}$ so that $0 \le i' \le 1$. If all exports were equally ecologically intensive all cells would be gray. The presence of darker and dashed darker cells shows that the inter-regional balance of trade in biophysical terms is disproportional to the balance of trade in financial terms. The heatmap provides a quick view of how closely the ecological balance of trade follows the financial balance of trade.

This heatmap visualization must be interpreted with caution for three reasons. First, it does not show the direction of trade, only whether the ecological and financial are the same direction. Second, because the color map is normalized for each indicator there will always be one dark gray cell, and if any reverse flows, one dark dashed red cell, in each subpanel. The heterogeneity of the cells is a truer indicator of ecologically unequal exchange. Finally, net export may not be the best measure of the ecological balance of trade. For example the financial net exports from Asia to Western Europe are not small because that trade volume is small but rather because that trade is nearly balanced. The ecological intensity of exports, discussed next, may be a better measure. Using the visualizations in Figs. 2–5 we conclude that Hypothesis 1, where biophysical terms are disproportional to the balance of trade in financial terms, is true, though not systematically or strongly so.

3.2. Hypothesis 2: Exports from Low-income Nations are More Ecologically Intensive than Those from High-income Nations

We visualize the ecological intensity of exports by income group (Fig. 6) and geographic region (Fig. 7). Indicator intensities for exports are normalized in the same manner as for net exports. We note several interesting findings. First, the ecological intensity of exports from low income nations and Africa is extremely high, especially compared to high income nations and Western Europe. If all exports contained the same embodied impact per dollar it would suggest that ecologically unequal exchange does not occur.

Latin America has relatively ecologically intensive exports measured in terms of embodied CO_2, HANPP, ecological footprint, and material flow. North America has relatively CO_2 intensive exports but is relatively clean as measured using the other indicators. The Middle East's CO_2 and material intensity can likely be explained by its fossil fuel industry and consequent large physical exports. Figs. 6 and 7 clearly show that Hypothesis 2, where exports from low-income

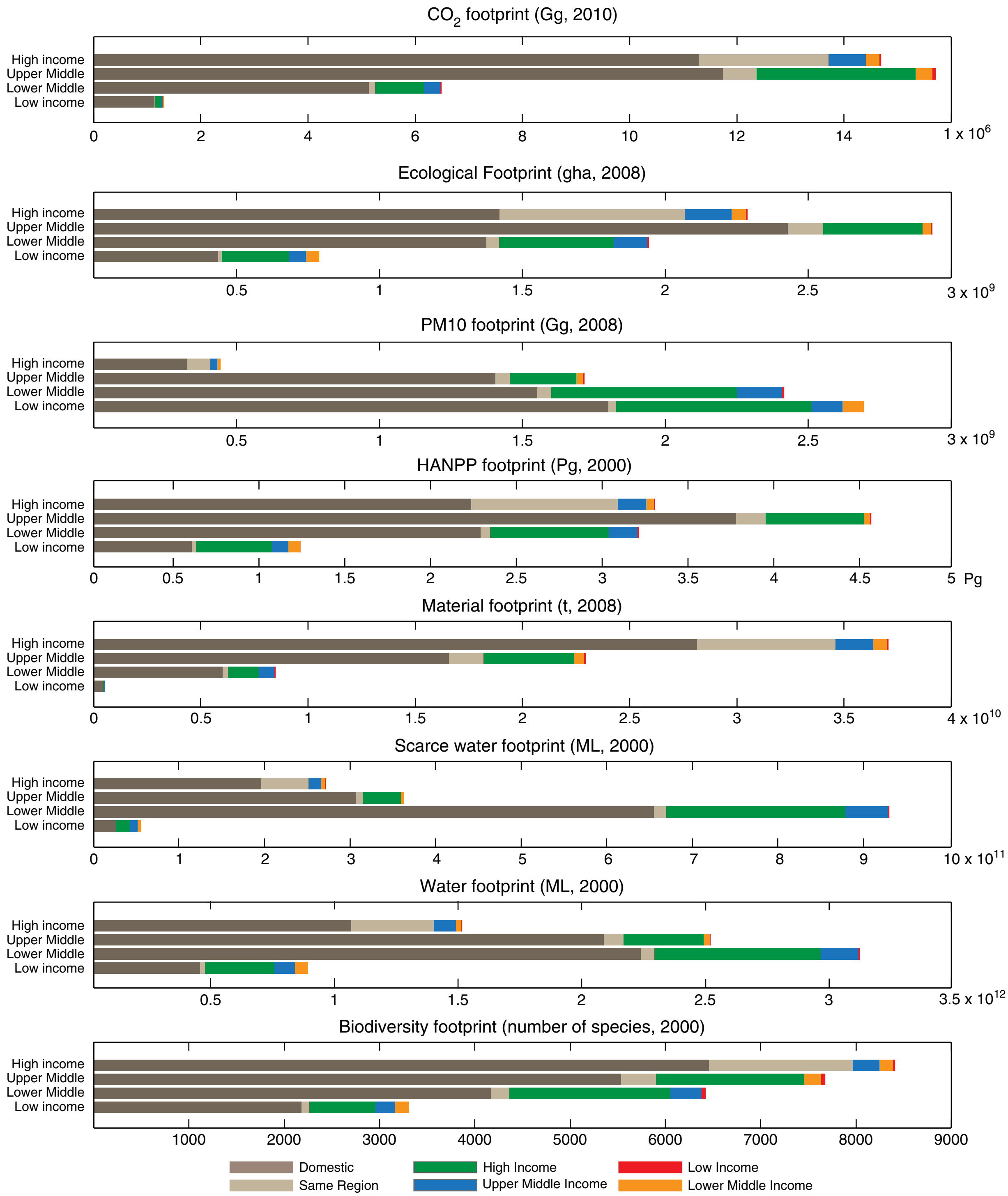

Fig. 9. Footprint, by source. Domestic footprint is exerted within the consumers' country; same region footprint is exerted within countries in the same income bracket, and the remainder of the footprint falls in countries of other income brackets. High income nations overwhelmingly export, not import, biophysical resources.

nations are more ecologically intensive than those from high-income nations, is true.

Four of the indicators have time series data available. The Eora MRIO models the economy and embodied flows using current USD, and when analyzing time series we have applied the US GDP deflator (World Bank, 2012) to correct for monetary inflation. For the four indicators for which a time series is available (CO_2, ecological footprint, PM10, and material footprint), we see that the exports are becoming less ecologically intensive (though the absolute environmental pressure is increasing). Low income nations, Africa in particular, have had more ecologically intensive exports for many years (or stated in the inverse, they have received a relatively low price for natural resources exported). As seen in Fig. 8, in nearly all cases the embodied CO_2, EF, PM10, and MF per dollar of exports have declined since 1990 (measured against real dollars, adjusted for inflation using the GDP deflator). However there are some exceptions in which flows became more ecologically intensive. The embodied material flow per dollar of exports from low income group countries to lower middle income group

Table 1
Change in footprint source between 1990 and 2007–2010 (end year varies by indicator).

Indicator	Consumers:	Footprint source: Domestic	Same region	High	Upper middle	Lower middle	Low
MF	High income	−7%	20%	–	88%	57%	17%
	Upper middle	−8%	54%	26%	–	15%	33%
	Lower middle	4%	−19%	0%	−20%	–	−5%
	Low	9%	−56%	23%	−73%	−46%	–
EF	High	−10%	12%	–	87%	49%	39%
	Upper middle	2%	39%	−15%	–	−24%	−32%
	Lower middle	−7%	8%	12%	71%	–	68%
	Low	−4%	61%	−1%	41%	−9%	–
CO_2	High	0%	−5%	–	39%	−19%	−67%
	Upper middle	−6%	24%	28%	–	−3%	−3%
	Lower middle	−1%	−16%	17%	−18%	–	47%
	Low	−2%	37%	19%	30%	−21%	–

countries increased. Embodied CO_2 in exports from Africa to the Middle East increased, as did embodied materials in African exports to other European countries. Latin American exports to other European countries, Asia/Pacific countries, and Africa, became more intensive in terms of embodied material use. The ecological intensity of exports from North America, Western Europe, and the Middle East has remained relatively constant since 1990, suggesting that for these countries marginal improvements in resource efficiency are difficult to achieve.

3.3. Hypothesis 3: High-income Nations Disproportionately Exert Ecological Impacts in Lower Income Nations

This hypothesis is perhaps the most fundamental in the debate over ecologically unequal exchange. In light of the previous results showing that exports from low-income nations are more ecologically intensive, we may expect this hypothesis to be true. In terms of CO_2 emissions many researchers are presently looking into this phenomenon of “burden shifting” or “leakage” (Davis et al., 2011; Peters et al., 2011), looking for evidence of whether CO_2 intensive industries will relocate to flee regulation, as air polluting industries have already done (Kanemoto et al., 2013). Whether high-income nations have lower carbon intensity of exports due to cleaner energy technology or due to the emigration of pollution industries is an unanswered question. In our earlier study of the biodiversity footprint (Lenzen et al., 2012b), we argued that high-income nations may have a relatively light biodiversity footprint embodied in their exports either because of better domestic protections (i.e. cleaner domestic technology), more advanced depletion, or the emigration of ecologically intensive production.

Despite this evidence suggesting that high-income nations exert a disproportional footprint on low-income nations, in absolute terms we find that low-income nations host a very small fraction of weather nations' footprints (Fig. 9). That figure plots the footprint of consumption by where the impacts from consumption originally occur: domestically (within the consumers' home country), within countries in the same income group, or in other countries in other income groups. The imported footprint of low, lower middle, and upper middle countries rests predominantly in high income, and to a lower extent, middle income, countries. In terms of embodied CO_2, ecological footprint, and material footprint we do see lower middle income countries as minor exporters. We see that only a small percentage (<1%) of imported footprint falls in low income countries, while high income countries host a much larger (up to 22%) share of the total footprint. The explanation must be that the large volume of relatively clean exports flowing out of higher income nations overrides the smaller volume of more ecologically intensive exports from lower income nations. This finding reconfirms our earlier study (Moran et al., 2009), but is still surprising.

For three indicators with time series data (CO_2, ecological footprint, material footprint), we find that the structure of footprint sources has not changed significantly since 1990. In relative terms low income and upper middle income nations export a larger footprint for foreign consumers today than in 1990. High income nations have a 39% larger ecological footprint in low income nations today than in 1990 (Table 1). However it is predominantly smaller flows

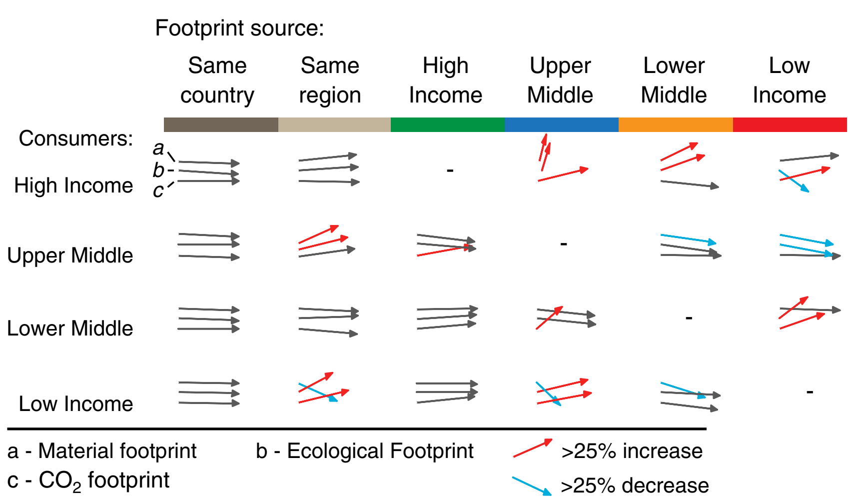

Fig. 10. Visualization of Table 1: Relative change in Footprint sources between 1990 and 2007–2010. Upper middle and Low income nations are today supplying an increased share of the natural resources used by consumers in other nations. Yet still the total embodied natural resource transfer out of these groups remains extremely small in absolute terms (compare to Fig. 9).

experiencing these large changes. The larger flows are more stable. Fig. 10 visualizes the relative change in footprint source between 1990 and 2007–2010.[5] The change in footprint supplied by upper middle and low income nations has increased in relative terms, yet in absolute terms this flow remains extremely small. The larger footprints supplied domestically, by countries in the same income bracket, and by high income countries, have changed less.

4. Discussion

Our findings suggest that the answer to the question, "does ecologically unequal exchange occur?" changes markedly depending on whether the answer is measured in terms of intensity, volume, or trend. This calls for more theoretical work to establish agreeable, testable hypotheses.

We conclude that when examined in terms of the balance of trade and ecological intensity of exports, ecologically unequal exchange does indeed occur, although we also find that the hypothesis that high-income nations disproportionately exert ecological impacts in lower income nations is false. Low income and African nations have much more ecologically intensive exports than other countries. In terms of export intensity the situation is generally stable or improving: lower income countries are receiving more dollars for their natural resources, though for the larger high-income economies the ecological intensity of exports has improved little since 1990. The overwhelmingly larger volume of exports from high income countries means that despite their ecologically intensive imports, high income countries are generally net exporters, not net importers, of natural resources. In relative terms high income nations do exert a disproportionately large footprint on low-income nations. But in absolute terms the opposite is true: high-income nations are net providers, not users, of ecological resources.

Why are high-income nations net exporters of natural resources? It could be a combination of higher productivity – French wheat farms produce 6.6 t/ha/yr while South African farms harvest just 1.7 t/ha/yr FAO, 2002 – or better endowments (perhaps indeed the reason these nations are more high-income). It is also possible that exports from high-income nations are cleaner because of more advanced depletion or stricter protection of remaining resources. In terms of air emissions, regulation is tighter, and in terms of biodiversity impacts, exports from less high-income nations may appear worse simply because those nations have a larger remaining stock of biodiversity.

Embodied resource flows are a social good when they help better allocate scarce resources. The trade in virtual water, for example, has been proposed as a solution to mitigate water scarcity (Allan, 1997). Yet at the same time embodied water in goods could allow wealthy consumers to purchase precious scarce water from lower-income countries (Lenzen et al., in press).

As globalization increases and international supply chains grow more numerous and more complex, consumers are ever further separated from their environmental impacts. Since their impacts are no longer local they may do less to reduce and mitigate their footprint. Furthermore, since natural resources are now sold to a global market the total size of impacts could be greatly amplified over what would occur if the market was purely domestic. This could be particularly concerning if natural resources are being sold too cheaply.

Consumption-based inventories, i.e. footprints, will play an increasing role in helping governments, businesses, and consumers understand their true resource dependencies. Without accounting for indirect flows it may appear that resource consumption is flat or declining, when in fact it is merely occurring abroad. Accurate inventories of actual resource dependency help account for current and expected future needs, help reveal risk in case critical resources are now coming from volatile sources, and together help markets put better current and future prices on ecological assets that are today most often underpriced.

[5] The end year varies per indicator depending on data availability; see Methods and Data.

Appendix A. Supplementary Data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2013.02.013.

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