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Analysis

Global patterns of ecologically unequal exchange: Implications for sustainability in the 21st century

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ABSTRACT

Ecologically unequal exchange theory posits asymmetric net flows of biophysical resources from poorer to richer countries. To date, empirical evidence to support this theoretical notion as a systemic aspect of the global economy is largely lacking. Through environmentally-extended multi-regional input-output modelling, we provide empirical evidence for ecologically unequal exchange as a persistent feature of the global economy from 1990 to 2015. We identify the regions of origin and final consumption for four resource groups: materials, energy, land, and labor. By comparing the monetary exchange value of resources embodied in trade, we find significant international disparities in how resource provision is compensated. Value added per ton of raw material embodied in exports is 11 times higher in high-income countries than in those with the lowest income, and 28 times higher per unit of embodied labor. With the exception of embodied land for China and India, all other world regions serve as net exporters of all types of embodied resources to high-income countries across the 1990–2015 time period. On aggregate, ecologically unequal exchange allows high-income countries to simultaneously appropriate resources and to generate a monetary surplus through international trade. This has far-reaching implications for global sustainability and for the economic growth prospects of nations.

1. Introduction

Global use of natural resources has reached unprecedented levels and is expected to further rise in the coming decades (Krausmann et al., 2018; OECD, 2018). International trade volumes have grown rapidly (Kastner et al., 2014; Wood et al., 2018) as domestic requirements for materials, energy, land, and labor have increasingly been met by drawing on non-domestic sources (Wiedmann and Lenzen, 2018; Wiedmann et al., 2015).

The advocacy of international trade is largely premised on the notion that such trade relations are economically beneficial to all parties (Feenstra, 2015). However, this perspective neglects the material aspects of international trade flows. In contrast, the theory of ecologically unequal exchange explicitly considers material aspects of international trade and postulates that there are asymmetric net transfers of resources (including labor) from peripheral to core areas of the global economic system (Hornborg, 2019, 2014, 1998). The exclusive focus on monetary flows implies a disregard for these potentially unequal transfers of biophysical resources, such as materials, energy, land, and labor, embodied in commodities and services traded between regions with differing economic 'power'.

High-income nations (the 'core' of the global economic system)

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depend on resource-intensive industrial technologies and infrastructures whose efficient functioning is contingent on annual net transfers of resources from distant (peripheral) areas (Frey et al., 2018; Jorgenson and Clark, 2009a). Moreover, high-income nations obtain significantly higher revenues for the resources they export than poorer nations, which is mostly due to the positions occupied in global supply chains and their respective roles in the world economy (Piñero et al., 2019; Prell et al., 2014; UNCTAD, 2013). The asymmetry of international trade, i.e. of the net transfers of resource volumes and monetary values, is a crucial determinant of the capacity of individual nations to accumulate capital and technological infrastructure and to thereby achieve economic growth (e.g., Grossman and Helpman, 1991).

Unequal trade patterns arise from and reproduce global socio-economic inequalities and hamper socio-environmental sustainability through environmental burden-shifting to poorer nations (Wiedmann and Lenzen, 2018). The displacement of extractive frontiers "elsewhere" (Schaffartzik and Pichler, 2017) is linked to socio-environmental conflicts and the rise of environmental justice movements particularly affecting the agricultural, mining, and manufacturing sectors (Temper et al., 2015) as well as commodified sinks for waste produced via economic activities (Hein and Faust, 2014).

To date, empirical evidence to support the theoretical notion of ecologically unequal exchange as a structural feature of the global economy is still very scarce. While there is a range of conceptual work (Hornborg, 2019, 1998) and of case studies that provide empirical evidence for the presence of ecologically unequal exchange between or within single nation states (Dorninger and Eisenmenger, 2016; Infante-Amate and Krausmann, 2019; Yu et al., 2014; Zhang et al., 2018), for specific commodities or indicators (Jorgenson, 2012; Jorgenson and Clark, 2009b), or in historical perspectives (Bogadóttir, 2016; Hornborg, 2006), comprehensive global assessments of ecologically unequal exchange over decadal time periods have not previously been undertaken. The results of the only global assessment – where ecologically unequal exchange was assessed in terms of proportionality of physical and monetary trade, ecological intensity, and net-transfers (Moran et al., 2013) – have been called into question (Dorninger and Hornborg, 2015). Given the increasingly globalized nature of the economic system and the increased focus on understanding teleconnections and sustainability (e.g., Friis et al., 2016; Seto et al., 2012), this represents a significant research gap for ecological economics and sustainability science. To fill this gap, this study assesses the international exchange of key resources at the global scale over a 26-year period (1990–2015). We quantify ecologically unequal exchange in four biophysical resources embodied in traded goods and services:

1) raw materials, expressed in 'raw material equivalents' (RMEs): materials directly traded plus all materials embodied in traded goods and services (measured in Gigatons [Gt]) (Schaffartzik et al., 2015);
2) energy: primary energy used along the whole supply chain to produce a certain good or service (measured in Exajoules [EJ]) (Owen et al., 2017);
3) land: land use that is directly and indirectly required for the production of a good or service (measured in hectares [ha]) (Bruckner et al., 2015); and
4) labor: all labor expended in the supply chain to produce a certain good or service (measured in person-year equivalents [$p\text{-}y_{eq}$]) (Simas et al., 2015).

To facilitate a global analysis of large-scale and diverse biophysical and socio-economic flows between countries, we use aggregated indicators that capture all materials, energy, land, or labor used in global supply chains.[1] In contrast to previous studies, we use biophysical resources, labor, and value added in one consistent framework and provide this in a time series analysis. Moreover, we conduct an inferential statistical testing of hypotheses derived from ecologically unequal exchange theory.

We use an environmentally-extended multi-regional input-output analysis (EEMRIO) to generate consumption-based pressure indicators ('footprints') in order to capture the displacement effects of international trade (Steinmann et al., 2017; Wiedmann and Lenzen, 2018). A national consumption footprint represents the domestic extraction (materials) or use (energy, land, labor) of biophysical resources within a given nation plus the net trade (imports minus exports, including embodied flows) (Wiedmann et al., 2015). The extractive expansion required for increasing trade volumes is often related to ecological distribution conflicts (Martinez-Alier et al., 2010).

In addition to the environment-related footprint assessments, we also used multi-regional input-output analysis to assess global monetary value chains and the analysis of trade in value added (TiVA). TiVA, which is sometimes referred to as a nation's 'value footprint' (Wiedmann and Lenzen, 2018), accounts for the monetary value added by one country embodied in the final demand of another country, i.e. TiVA represents the monetary value a nation generates through its exports rather than the total value of the goods exported (Stehrer, 2012). The TiVA indicator is the financial counterpart to input-output-based resource footprints and follows the same calculation steps (see Section 3.2). To the best of the authors' knowledge, the present study is the first to analyze embodied resource flows and TiVA in one consistent framework.

Our analysis is based on the most recent data available from the EEMRIO database Eora (Lenzen et al., 2012b, 2013b). In addition to direct international trade flows, EEMRIO models allow calculating embodied resource flows associated with global supply chains, by including the intermediate resources used to produce goods and services for final demand (Wiedmann and Lenzen, 2018; Wiedmann et al., 2015). We analyze the domestic extraction and use of resources and their reallocation through international trade on a global scale and in a temporal perspective. We calculate net international appropriation as well as differences in monetary valuation (TiVA) of materials, energy, land, and labor. Further, we build four structural equation models (SEM), one for each of the examined resources, to statistically assess relationships between predictive socio-economic variables, resource appropriation, and value added generation as suggested by ecologically unequal exchange theory.

Our analysis includes 170 countries, encompassing 99.2% of the world population in 2015, and the bulk of global supply chains and economy-wide resource flows. In order to investigate patterns of trade in relation to income inequality, we group countries into four income classes based on gross national income (GNI) per capita. Inspired by the World Bank's classification of income and lending groups (World Bank, 2018a), we refer to them as high-income (HI), upper-middle income (UMI), lower-middle income (LMI), and low-income (LI) countries. However, in order to maintain similarly sized groups in terms of total population, our income boundaries deviate slightly from those of the World Bank (for details see Appendix B, Fig. 5 and Table 1).

2. The theory of ecologically unequal exchange

The only concept of 'unequal exchange' that is recognized by conventional economics refers to market power, that is, obstacles to the unrestrained operation of price-setting market mechanisms. The theory of *ecologically* unequal exchange proposes that in addition to market

[1] Note that other research contributions have examined additional flows that are embodied in international trade of goods and services that we do not focus on in this study, e.g., embodied water (Lenzen et al., 2013a), biodiversity (Chaudhary and Kastner, 2016; Lenzen et al., 2012a), or emissions and waste flows (Dalgaard et al., 2008; Oita et al., 2016).

power asymmetries there are neglected asymmetric transfers of biophysical resources. The theory argues that such asymmetric resource flows are crucial for the capacity of cities, nations, and regions to accumulate technological infrastructure and achieve economic growth (Hornborg, 2018, 2016). However, asymmetries in transfers of material resources on the global market are generally not considered significant for the growth potential of individual nations. This suggests a major conundrum in economic thought, as the infrastructures of urban and industrial areas that are indexical of growth are incontrovertibly material. To provide an exhaustive account of economic growth, ecologically unequal exchange theory argues, the net transfers of material resources must be included. This, in turn, implies that metrics other than monetary exchange-value need to be considered, such as tons of materials, hectares of land, person-year equivalents of labor, or Joules of energy (Hornborg, 2019).

Heterodox schools of economics such as Marxism and ecological economics have proposed that asymmetric resource flows are essential for a nation's prospects of economic growth. Arghiri Emmanuel (1972) focused exclusively on the unequal exchange of embodied "labor value" in international trade, arguing that discrepancies between the price of labor in different countries results in net transfers of embodied labor time from low- to high-wage countries. Stephen Bunker (1988) proposed that there was also an unequal exchange of "energy values" that benefitted industrialized regions to the detriment of extractive zones of the world economy.

The theory of ecologically unequal exchange does not contradict the mainstream definition of value as based on exchange-value (utility) determined by the market, but adds that the inevitable attribution of higher value to commodities representing lower remaining productive potential (or "negative entropy", see Georgescu-Roegen, 1971) inexorably leads to asymmetric transfers of resources. This definition of unequal exchange does not suggest that market evaluations systematically neglect some more fundamental measure of value, as do labor and energy theories of value, but rather that they lead to rising environmental impoverishment in extractive sectors and regions.

The theory of ecologically unequal exchange proposes that countries rich in economic, technological, or military power are more likely to gain access to resources (materials, energy, land, and labor) that are relevant to achieve economic growth and to build technological infrastructure. As a result, resources flow asymmetrically, with net-transfers from poorer to richer regions. As described above, the theory further posits fundamental differences in how resources around the world are compensated, i.e. resources of richer regions are compensated higher compared to those of lower-income regions. Both these trends are predicted to be of self-perpetuating character (Hornborg, 2019; Jorgenson and Clark, 2009b). The awareness for ecologically unequal exchange is more widespread in some world regions, specifically within the debate on extractivism and the 'ecological Prebisch thesis' in South America (Pérez Rincón, 2006; Samaniego et al., 2017), or in Africa (e.g., Amin, 1972). A recent overview of the broad range of scientific literature that theoretically elaborates the concept of global ecologically unequal exchange is provided by Givens et al. (2019).

In this article, we empirically demonstrate the occurrence of ecologically unequal exchange and argue that economic theory must acknowledge material aspects of the economy shaping the relationship between economic growth and sustainability. From the perspective of ecologically unequal exchange theory, major contemporary challenges of sustainability are predictable consequences of economic globalization and the operation of the global market. These challenges include: rising economic and social-ecological inequalities (Alvaredo et al., 2018; Piketty, 2014; Prell et al., 2017), socio-environmental burden-shifting to poorer regions and ecological distribution conflicts (Martinez-Alier et al., 2010; Warlenius et al., 2015), and the outsourcing of resource-intensive production rather than curbing resource use in the high-income nations (Jiborn et al., 2018; Schandl et al., 2018; Wiedmann et al., 2015).

3. Materials and methods

We apply EEMRIO methodology and structural equation models (SEM) to quantitatively test the hypotheses derived from the theory of ecologically unequal exchange. As mentioned in the introduction, we group the countries of the world into four income groups based on gross national income (GNI) per capita. Separating India and China allows to form income groups of relatively even population size – which is fundamental when aiming to analyze relations between rich and poor. The high-income (HI) countries make up 15.5% of the world population in 2015, the upper-middle income (UMI) countries 16.1%, the lower-middle income (LMI) countries 15.7%, and the low-income (LI) countries 15.3%. China's share of the world population in 2015 was 18.7% and that of India 17.8%. More details on the country classification can be found in the Appendix B, Fig. 5 and Table 1.

3.1. Environmental input-output analysis

Input-output analysis (IOA), originally conceived by Nobel Prize Laureate Wassily Leontief (1936), is based on monetary input–output tables (IOT), which describe interdependencies in the economy by recording transactions among industries (Z), supply of final demand (y) and value added in production (v).[2] The core principle in IOTs are monetary industry balances, where total output must be equal to total input per industry. Henceforth, capital and minor letters respectively denote matrices and column-vectors, the prime indicates transposition. Total output (x) equals all sales for intermediate production plus final demand, that is, $x = Zi + y$, whereas total input (x') equals all inter-industry purchases plus value added, $x' = i'Z + v$. Note that i is a column-vector of ones used for summation, hence Zi sums the row elements in the transaction matrix and $i'Z$ the elements in the column. On the basis of input–output tables, the demand-driven IO model can be estimated by

$$x = (I - A)^{-1}y = Ly$$

where $A = Z\hat{x}^{-1}$ is the matrix of direct input coefficients i.e. the technology matrix, whose element $a_{ij} = z_{ij}/x_j$ expresses direct inputs from industry i per unit of total output of sector j. I is the identity matrix. Hats (ˆ) indicate diagonalization of vectors, and $\hat{x}^{-1}$ denotes matrix inversion of $\hat{x}$. $L = (I - A)^{-1}$ is the 'Leontief inverse', whose element l_{ij} quantifies the total upstream i.e. direct and indirect inputs from sector i that are required to produce a unit of industry output j for final demand.

Multi-regional input-output (MRIO) tables integrate national IOTs and bilateral trade accounts and contain data for hundreds of countries. MRIO analysis is frequently concerned with the assessment of environmental pressures embodied in international trade (Wiedmann and Lenzen, 2018). A number of global MRIO databases have been developed over the last decade. The present study uses the full MRIO database Eora (Lenzen et al., 2012b, 2013b)[3] for three reasons: its high country resolution (189 countries), the availability of time series data (from 1990 to 2015), and the disaggregation of products and industries (between 26 and 500).

Monetary IOTs are complemented by extension tables (e) recording non-monetary flows associated with economic activities, such as raw material extraction (measured in metric tons), direct energy (Joule), land use (hectares), and labor requirements (working hours). Extension tables are sometimes referred to as the production-based account. Consumption-based accounts (F) are calculated by $F = \hat{q}L\hat{y}$, where $q = e\hat{x}^{-1}$ is an intensity vector showing the direct use of non-monetary flows (e) per unit of industries' total output (x). Element f_{ij} quantifies the amount of non-monetary flows (e) that are embodied in the total

[2] Value added in production accounts for the compensation of employees, depreciation of fixed capital, profits plus taxes minus subsidies.

[3] Version v.199.82 (available at http://www.worldmrio.com/).

upstream inputs from industry i required to satisfy the final demand for industry output j (for further details see Miller and Blair, 2009). Consumption-based accounts (F), when calculated in an IOA framework, always add up to the total production-based account (e). In other words, non-monetary flows are allocated to final demand without double-counting.

3.2. Trade in value added (TiVA)

To compare the value added from international trade over time we use TiVA (Johnson and Noguera, 2012; Timmer et al., 2014) in constant international 2010 US-American dollars (USD). The TiVA concept is motivated by the fact that monetary databases on bilateral gross trade flows do not accurately measure the amount of value added exchanged between countries, i.e. the original source country of the value-added. In monetary terms, trade in intermediates accounts for approximately two-thirds of international trade (Johnson and Noguera, 2012). In the era of globalized supply chains, imports (of intermediates) are used to produce exports and hence bilateral gross exports may include inputs – i.e. value added – from third party countries. TiVA reveals where (e.g. in which country or industry) and how (e.g. by capital or labor) value is added, i.e. captured or created, along global supply chains (Timmer et al., 2014).

Calculating monetary bilateral trade flows on the basis of TiVA is fully consistent with the IO-based footprint concept because both indicators follow the same system boundaries, quantifying two properties (financial and physical) of the same object (all supply chains between production and final consumption of two countries including all direct and indirect interlinkages). In contrast to global bilateral monetary trade flows, TiVA is globally balanced, meaning that national exports and imports globally sum up to zero. From a conceptual point of view, monetary bilateral gross trade flows, as reported by UN-Comtrade, IMF and WTO, should be used mainly for assessments of direct physical trade flows.

Using a demand-driven IO model as described before, a value added footprint i.e. TiVA indicator (B) is calculated by $B = \hat{p}\,L\hat{y}$, where $p = v\hat{x}^{-1}$ is a vector showing the amount of value added (v) per unit of industries' total output (x). The sum of the columns elements adds up to final demand ($y = i\,'B$) and the sum of the row elements to value added ($x = Bi$), no double-counting involved. Global value added (v) sums up to global final demand (y). In 2015, this was approximately 75 trillion USD. Consequently, element b_{ij} quantifies how much value added (v) is embodied in the total upstream inputs from industry i required to satisfy the final demand for industry output j. We can interpret the element b_{ij} as an indicator showing how much of the expenditures of final demand for industry output j is directly and indirectly captured by the production activity of industry i.

3.3. Structural equation models (SEM)

We used piecewise structural equation models (SEM) to put the hypotheses from the theory of ecologically unequal exchange to a rigorous quantitative test. SEMs are networks of variables connected through paths that represent statistical relationships (Grace, 2006; Lefcheck, 2016). The main feature of SEM is that variables can simultaneously take the roles of predictors and responses. The SEM approach models indirect effects between two variables that are mediated by other variables, which is sometimes also referred to as 'cascading effects' (e.g., Dorresteijn et al., 2015). Piecewise SEM has been developed only recently (Lefcheck, 2016), and has the benefit of being more flexible than traditional SEM. Traditional SEM methodology is based on a global estimation of the variance-covariance matrix implied by the model specified. Global estimation however limits the statistical flexibility available in specifying the model components. Piecewise SEM removes this limitation by resorting to local estimation of constituting regression models. As a result, the structural equations of the model, may be any kind of generalized linear model or generalized linear mixed model, which enables statistical modeling of specific types of data that could not easily be handled by the traditional approach, such as count data or truncated data.

We construct our SEM for the year 2015 from a set of linear and generalized linear regression models. Linear models were possible for all net import variables and the technological power model. For all value added models as well as for per capita GNI and military expenditure, we used generalized linear models (GLMs) with a Gamma error structure and log-link function. Thus, prior to interpretation, GLM coefficients have to be exponentiated (with base e) to yield a multiplier that indicates the factor applied to the expected value of the response when the predictor changes by one unit.

We used income (GNI), a technology adoption index (World Economic Forum, 2016), military expenditure (World Bank, 2018b), and biophysical reserves, i.e. the total fossil fuels (U.S. Energy Information Administration, 2018) and metal ores reserves (U.S. Geological Survey, 2015), plus the national actual terrestrial net primary productivity (NPP_{act}) expressing biomass reserves (Haberl et al., 2007), as independent variables (representing economic, technological, and military power, as well as natural resource endowment) and net imports of resources and the TiVA generated per resource unit embodied in exports as dependent variables.

We performed all statistical analyses in the R environment (R Core Team, 2019), making use of the 'piecewiseSEM' package (Lefcheck, 2016). All SEM diagrams were drawn using the web-based visualizing tool 'draw.io' (www.draw.io).

3.4. Limitations

Our study design has potential limitations related to the operationalization of the theory, the methods and data used. We focus on hypotheses from ecologically unequal exchange theory that could be tested with the data available. Other hypotheses of ecologically unequal exchange theory such as those regarding historical emergence or within-country appropriation could not be tested. For example, it should be noted that the 'gaining of access' to resources is not only an international process. The unequal exchange between nation states is preceded by an unequal appropriation by core-like areas within nation states, especially in larger countries like Brazil or India (Martinez-Alier et al., 2016). And these phenomena of intra-country inequality and distribution (Wiedenhofer et al., 2017) cannot be grasped by a country-level analysis.

We use SEM methodology to approach drivers and statistical relationships of the ecologically unequal exchange phenomena. The usual disclaimers for statistical modeling do apply for piecewise structural equation models in particular. First and foremost, while we find a good fit of our models to the data, this does neither imply that all models are correct, nor is it a proof that the theory of ecologically unequal exchange is true in reality. Second, and related to the first point, the models used in our analysis are to be understood as an approximation of reality (Abelson, 2012; Grace, 2006), and we have not considered other approximations, i.e. model candidates. This confirmatory approach is appropriate for the purpose of testing a set of hypotheses from a particular theory as we have aimed for here, but it has to be kept in mind that a candidate modeling approach and multimodel inference would likely be more useful for predictive purposes (Burnham and Anderson, 2004; Grueber et al., 2011).

The data availability to represent a country's "technological infrastructure", as described by the theory of ecologically unequal exchange, is limited. We have chosen to use the "technological adoption index" of the World Economic Forum (2016) which is available for almost all countries of the world and which measures the "agility with which an economy adopts existing technologies" (World Economic Forum, 2016). However, a global data source representing more directly a country's endowment with technological infrastructure would certainly increase the validity of results of the SEM even more.

Regarding uncertainties in EEMRIO, it must be noted that environmental footprint results can differ for many reasons, often rooted in the specifics of how the underlying databases are constructed. EEMRIO models can have varying levels of geographical resolution or sector aggregation that can have significant impacts on footprint results (de Koning et al., 2015; Piñero et al., 2015) and, when constructed from supply-use tables, use different technology assumptions (Majeau-Bettez et al., 2014). However, studies comparing EEMRIOs revealed that differences in the environmental extensions are the most important cause for differences in the footprints of nations (Owen et al., 2016, 2014; Tukker et al., 2018). After harmonizing the environmental extensions between different EEMRIOs, carbon footprint results for most major economies disagree by < 10% (Moran and Wood, 2014) and material footprints by < 15% (Giljum et al., 2019).

4. Results

4.1. Production and consumption perspectives on resources and TiVA

Across the embodied flows of materials, energy, land, and labor, the group of HI (high-income) countries used more resources from a consumption perspective than they provided through production in the year 2015 (Fig. 1a–d). Their final demand was associated with raw material requirements (including embodied resource use) exceeding their domestic extraction by 10 billion tons per year (Gt/a, 1 Gt = 10^9 metric tons). All regions except for HI countries were net providers of raw materials, with their production exceeding their consumption of resources. The largest net exporter of RMEs is the group of UMI nations (4.3 Gt/a) (Fig. 1a).

HI nations were both the largest domestic producers of primary energy (203.9 Exajoule per year (EJ/a), 1 EJ = 10^{18} J) and the main net appropriators of energy embodied in traded goods (22.7 EJ/a), resulting in a very high energy footprint (226.6 EJ/a). Energy – that is, almost exclusively fossil energy – appropriated by HI countries mainly stemmed from the UMI countries and China (Fig. 1b). Next to the HI countries, the only other net-appropriation occurred in the LI countries, although at a very low level of about 0.5 EJ/a.

The HI countries were also the largest net appropriators of land (of approximately 0.8 billion hectares per year). Their land footprint corresponded to 31% of total global land used (Fig. 1c). Together with the HI countries, China and, to a lesser extent, India were net appropriators of embodied land, while the UMI, LMI and LI countries were net providers. Nonetheless, the UMI countries maintained the largest land footprint.

All income groups but the HI countries were net providers of labor (Fig. 1d). China, with a high level of domestic labor use, exhibited the largest international net provision of embodied labor (74 person-year equivalents per year) (p-y_{eq}/a), followed by India with net exports of 47 million p-y_{eq}/a in 2015. In comparison, the HI countries net appropriated 182 million p-y_{eq}/a.

In 2015, HI countries achieved a monetary trade surplus[4] and, at 48.5 trillion USD, not only by far the highest value added (TiVA), but more than all other income groups, including China and India, combined (26.7 trillion USD) (Fig. 1e). Next to the HI countries, only China achieved a monetary trade surplus (in terms of value added) in 2015. However, while China exhibited a trade deficit in terms of natural resources (except for embodied land), the HI countries were a net importer of all resources assessed. In 2015, well over half of global TiVA was *between* high-income countries while, as we have demonstrated in Fig. 1a-d, materials, energy, land, and labor notably flowed from all other country groupings to the HI countries.

[4] Note that this is an aggregate number. Not every single HI country experiences a monetary trade surplus in 2015.

Whereas each country and country grouping represent a roughly similar population size, the lower-income countries (LMI, IND, LI) play a relatively marginal role in international trade, which is also due to their overall lower domestic extraction and use of resources. This applies to all of the examined resource flows and becomes particularly evident with TiVA where the HI countries (15.5% of world population in 2015) account for more than two-thirds (64.5%) of the global value added.

4.2. Temporal persistence: annual net trade and accumulated appropriation and provision

Compared to their population, HI countries net appropriate a disproportionately large share of materials, energy, land, and labor through international trade (Fig. 2). This disproportional distribution grew from 1990 until the 2007/8 global financial crisis, requiring ever-larger net provisions from the rest of the world. The financial crisis was associated with reductions in the net appropriation of all four resources by HI countries. However, they remained the only significant net appropriators. Rising appropriation by HI countries was mirrored by rising provision by, i.e. exports from, China. The expansion of net exports of RMEs and embodied energy was especially pronounced in the UMI countries and coincided with relatively stagnant net provisions of embodied land and labor. LI countries were the primary net providers of embodied land, with rapid increases during the 1990s.

While acting as a net appropriator of embodied resources, the group of HI countries was able to accumulate a monetary trade surplus (positive TiVA) of approximately 1200 trillion USD over the 1990–2015 time period. China achieved an even higher monetary trade surplus (approximately 1900 trillion USD). However, unlike the HI countries, China acted as a net provider of embodied materials, energy, and labor. In general, the temporal patterns of TiVA net trade exhibited considerably less stability than the trade of resources and there was a less marked difference between high and low-income country groups.

4.3. Monetary valuation of embodied resources

The asymmetry in the distribution of monetary value added is especially apparent in the direct comparison between embodied resource flows and TiVA (Fig. 3). With lower per capita income, value added per unit of exported embodied resource is generally lower. This inequality was found for all four resources assessed and particularly pronounced for embodied labor. However, China often obtained more TiVA per unit of exports than the UMI group and, for land, also more than the HI group since 2010.

The HI countries generated significantly higher levels of TiVA per unit of exported RMEs than all other income groups. This trend is apparent throughout the analyzed period and does not decrease over time. HI countries tend to receive more than double the TiVA per embodied energy exported than the poorer countries.

For land, the HI countries are not the only group with high TiVA per unit of land embodied in exports. Because of low export flows of embodied land (making them net-importers of embodied land overall, Fig. 1c and Fig. 2c), the high TiVA in China's case and even India's stagnating TiVA give these countries comparatively high TiVA/ha of embodied land (Fig. 3c). For the other income groups, and especially for the LI nations, the TiVA from exports of embodied land remained very low compared to HI countries, China, or India. This is the result of the LI countries acting as major providers of land while receiving far less TiVA than any of the other country groups.

In terms of compensation for embodied labor, there are, again, tremendous differences between HI countries and the rest of the world. During this 26-year period, HI countries gained on average 12 times more TiVA per labor unit (p-y_{eq}) embodied in exports than the rest of the world.

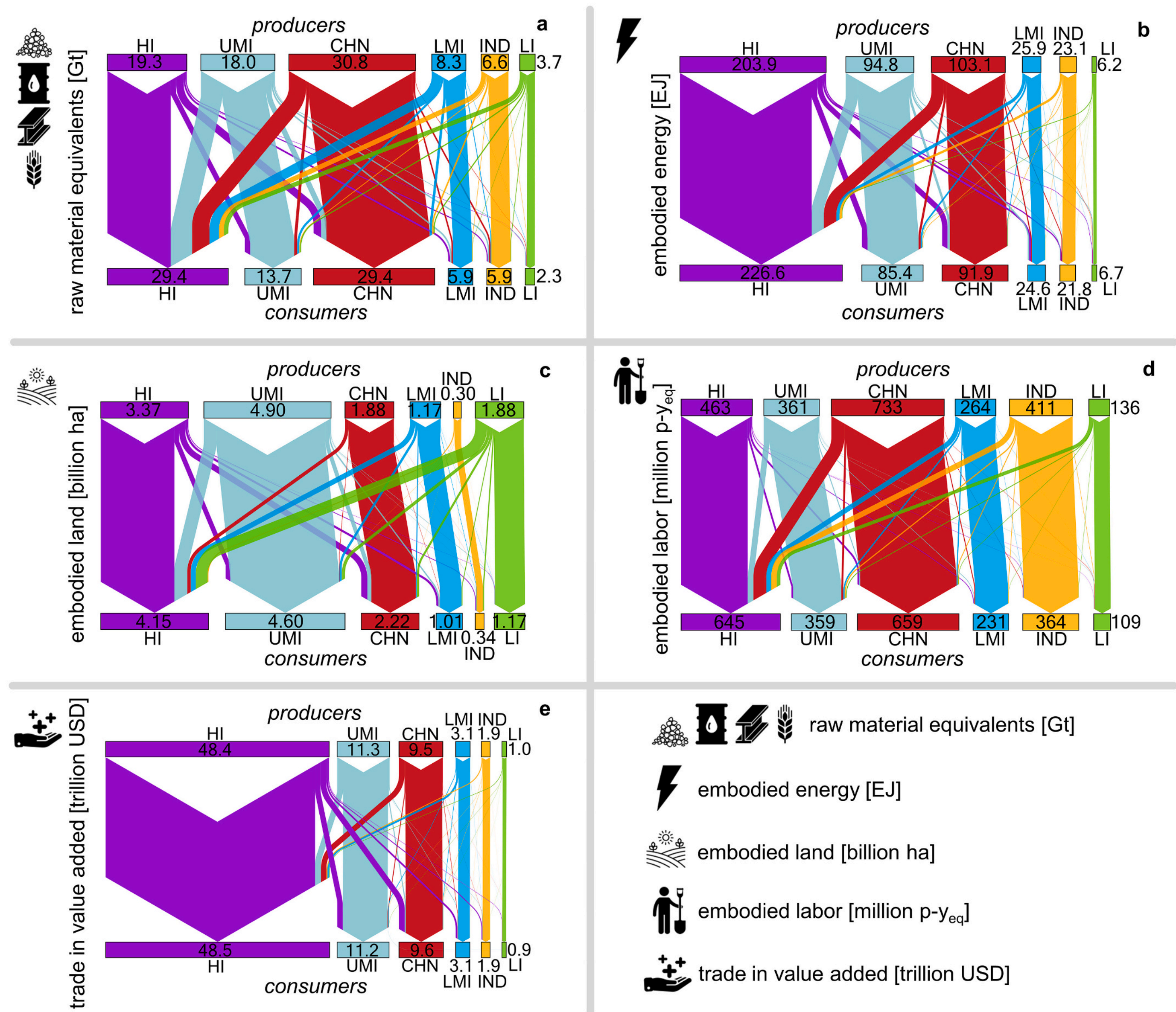

Fig. 1. Sankey diagrams exhibiting production and consumption of resources in each income-based country grouping (high-income HI, upper-middle income UMI, lower-middle income LMI, low-income LI), China (CHN) and India (IND) in 2015. Flows represent the redistribution of resources through trade. Note that money (as consumer expenditures) and resources flow in opposite directions in trade relations, i.e. money flows from consumers to producers. However, embodied value added (TiVA) is aligned in the same direction as embodied resources (e).

4.4. Drivers and statistical relationships of ecologically unequal exchange

Fig. 4 shows four structural equation models (SEMs) which test hypotheses in the form of statistical relationships between independent (economic, technological, military power, and natural resource endowment) and dependent variables (net imports of resources and TiVA generated with exports). All data for the SEMs are available in the supplementary material.

Fit statistics indicate that the hypothesized model provides an adequate description of the data, both with respect to overall model fit ($p = 0.63$, Fisher's $C = 2.57$) as well as variance in the data explained by individual model regressions (as indicated by the respective Nagelkerke-R^2 values[5]). Of the 13 directed relationships, ten were found to be likely non-zero. The fit of our model to the data suggests that nations tend to become net importers of raw material equivalents (RMEs) with growing income. For each additional 1000 $ GNI per capita, we estimate an increase in net imports of RMEs of 0.4 tons per capita. Conversely, for each kiloton of biophysical resources available as reserves per capita, a country's net RME imports decline by 8.1 tons per capita. With regards to exports, income has a positive effect on the TiVA per RME exported. We find that for an additional GNI of 1000 $ per capita, a country can be expected to increase the value added per ton of RME exported by 52 USD. Military strength, as measured by the annual governmental military expenditure per capita (World Bank, 2018b), had a negative effect on net imports of RMEs. Technological

[5] Strictly speaking, Nagelkerke's likelihood-based R^2 (Nagelkerke, 1991) measures the improvement in fit of the model specified over the null model (intercept-only model). That is, values closer to 1 indicate larger improvements

(*footnote continued*)
over the null model than smaller values. The resulting value is thus also a measure of how well the variability in the dependent variable can be explained by variability in the independent variables.

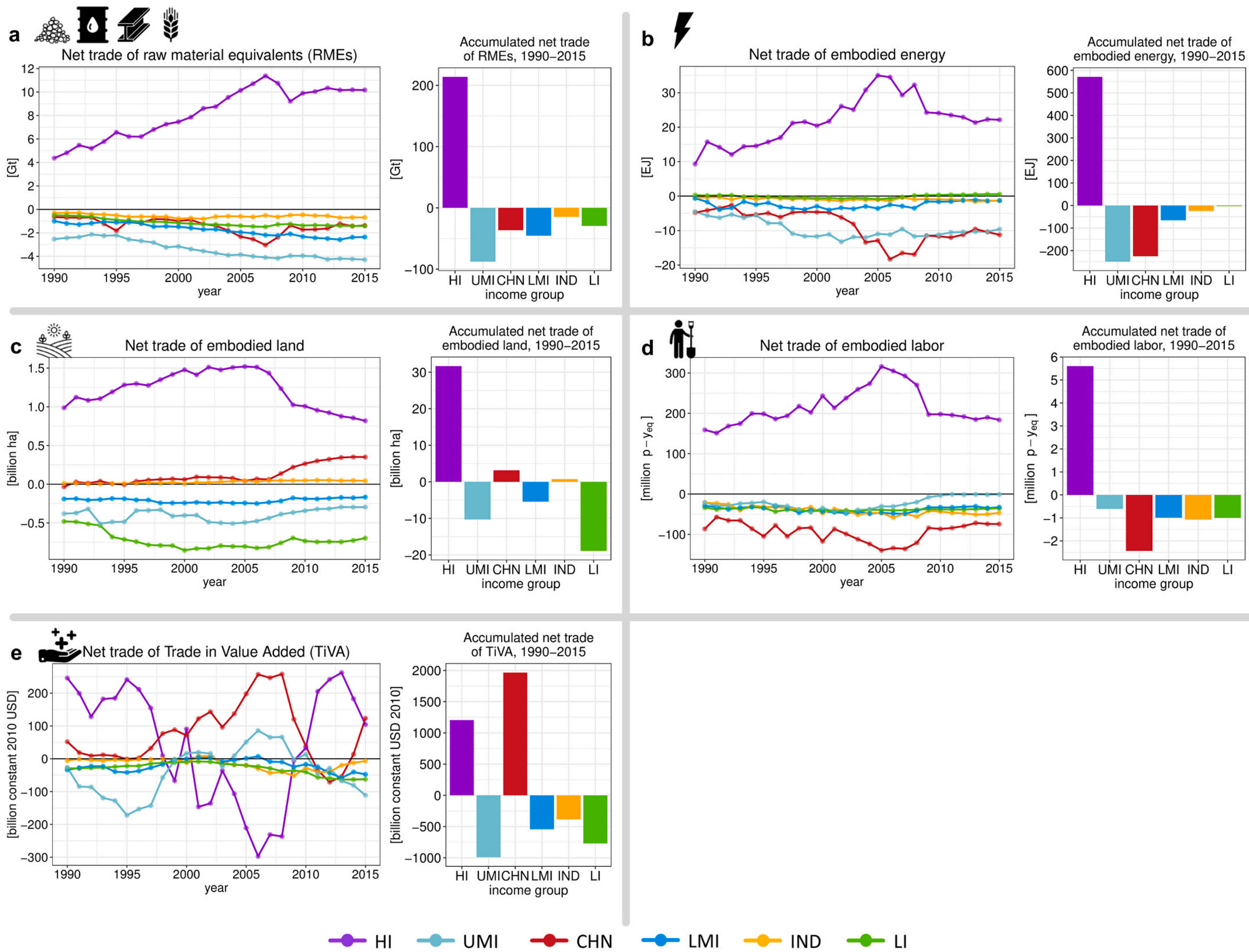

Fig. 2. Net trade of resources over time and accumulated appropriation and supply as bar plots, 1990–2015. a: raw material equivalents (RMEs) [Gt]; b: embodied energy [EJ]; c: embodied land [billion ha]; d: embodied labor [million p-y_{eq}]; and e: trade in value added (TiVA) [bn constant 2010 USD]. Positive values represent a net appropriation of resources.

power, as represented by a country's technological adoption index of the World Economic Forum (2016), neither had a significant effect on per capita net imports of RMEs nor on value added per RME exported (Fig. 4a).

The SEM for embodied energy ($p = 0.3$, Fisher's $C = 4.88$) does not exhibit significant effects of biophysical reserves and GNI on the net import of embodied energy, and only 5% of the variability in the data on net imports of embodied energy was explained by the model. However, higher income and net imports of embodied energy both had a positive effect on TiVA per exported unit of energy. Our model indicates that higher military expenditure implied on average lower TiVA per embodied energy unit exported (Fig. 4b).

The SEM for embodied land ($p = 0.52$, Fisher's $C = 3.21$) shows a positive impact of per capita GNI on net imports of embodied land, albeit a rather small one (0.0001 ha per capita per 1000 $/cap increase). For comparison, in 2015 the land footprint for HI countries was 3.63 ha/cap/a and they had a net import of 0.68 ha/cap/a, for LI countries the footprint was 1.04 per/ha/a while they net exported 0.61 ha/cap/a. A 1 ha/cap increase in net imports of embodied land implies an increase in value added by 160 USD per ha of embodied land exported (Fig. 4c).

The SEM for embodied labor and its TiVA ($p = 0.78$, Fisher's $C = 1.78$) is the only one of our models which does not yield a positive relationship between net imports and value added (Fig. 4d). For each 1000 $/cap increase in GNI, net imports of embodied labor tend to rise by 0.006 p-y_{eq}. With the same increase in GNI, the TiVA per embodied labor [p-y_{eq}] exported increases by 56 USD. The richer a country, the greater the net appropriation of embodied labor and the more it received for the embodied labor it exported. Conversely, the poorer a country, the larger is its net exports of embodied labor, but the less it receives per unit of embodied labor exported.

From the four SEMs we conclude that the crucial variable determining access to resources and trade in value added for exports was economic power, i.e. per capita GNI. By contrast, military power did not play a role (or had a negative effect). However, per capita GNI had a positive impact on both military expenditure and technological adoption. The effect of income outweighs other potentially significant effects of technological or military capacity. Hypothesis testing, in general, can only ever fail to reject a theory, and there is good evidence here to justify maintaining ecologically unequal exchange theory.

5. Discussion: implications of ecologically unequal exchange

The theory of ecologically unequal exchange posits the disproportionate access of high-income countries to resources. Our analysis shows how the creation of (monetary exchange) value added in HI

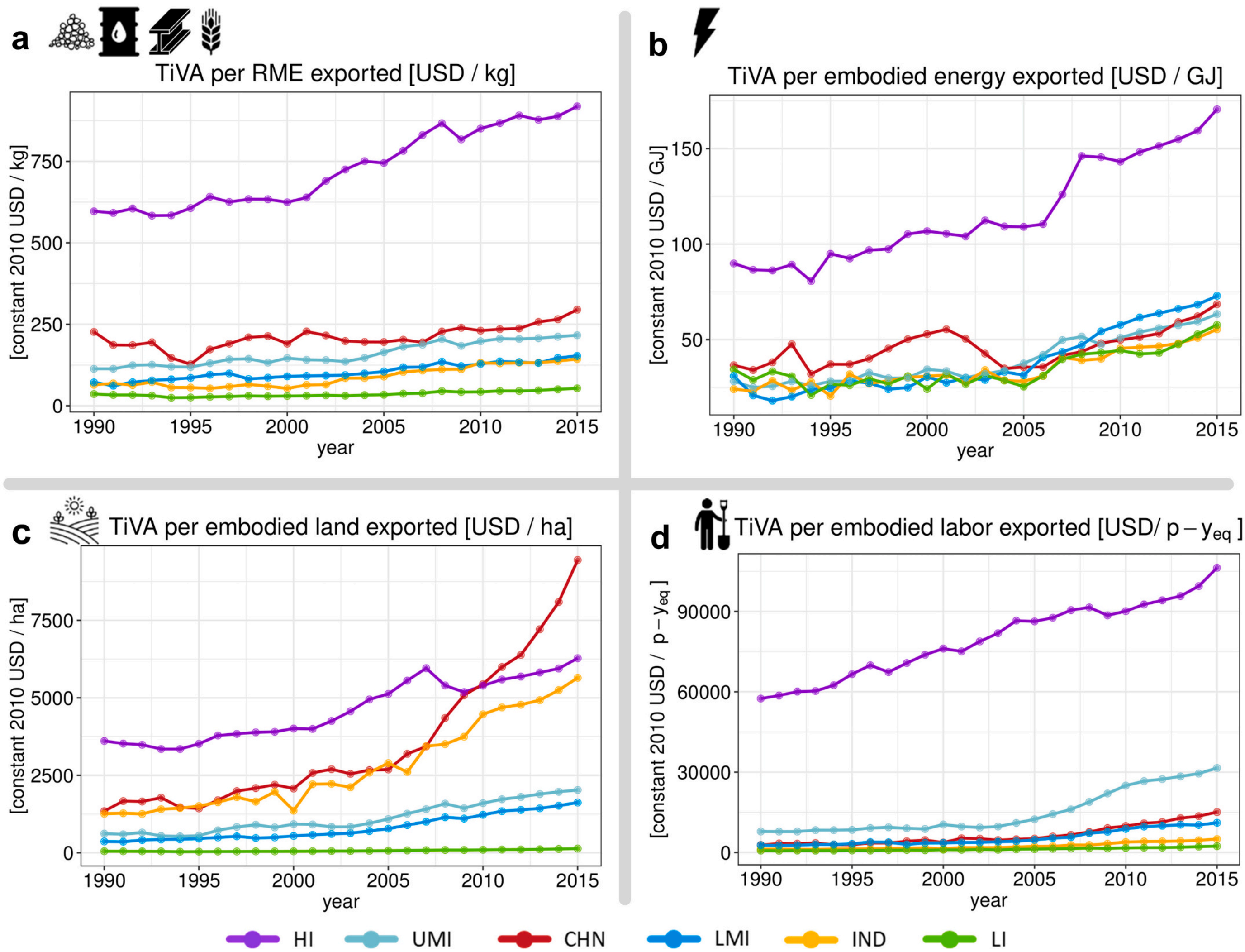

Fig. 3. Trade in value added (TiVA) of resources embodied in exports, 1990–2015, in constant international 2010 USD. Top left: value added per raw material equivalent (RME) exported [USD per t]; top right: value added per unit of embodied energy exported [USD per GJ]; bottom left: value added per hectare embodied in exports [USD per ha]; bottom right: value added per labor equivalent embodied in exports [USD per p-y_{eq}].

nations depends on the annual net inflow of resources from lower income regions. This observation holds true for the entire period observed, suggesting that this asymmetric exchange is a structural feature of trade relations and that economic growth in HI nations has not decoupled from such unequal exchange relations.

Methodologically, we go beyond other recent treatments of the subject matter that have used simple multiple regression to model material footprints (e.g., Wiedmann et al., 2015) or descriptive approaches to material flow accounts (Krausmann et al., 2018). Ecologically unequal exchange theory postulates a complex interplay of variables rather than a set of internally unconnected relationships between key variables. Our use of piecewise structural equation models is the first direct empirical test of hypotheses generated by ecologically unequal exchange theory at the global level.

With regards to driving factors of ecologically unequal exchange, our structural equation models indicate that while military expenses and technological adoption are both highly significantly positively affected by GNI, they most often do not have significant positive effects on either the net-import of resources or the TiVA of exports. The effect of income outweighs potential other significant effects of technology or military. What is more, the negative effect of governmental military spending on the net-imports of RMEs suggests that current military expenditure might not be the decisive element to ensure access to internationally traded resources. Interestingly, the significant negative effect of biophysical reserves on technological adaptation indicates that countries rich in biophysical resources tend to fall behind in technological development, a possible indication for the global presence of the much-debated "Natural Resource Curse" (Ross, 2015; Venables, 2016).

We find significant differences in the monetary compensation of materials, energy, land, and labor embodied in traded goods. These differences were mostly determined by the countries' income level, implying that poorer countries hold positions in global supply chains that determine low monetary compensation for resources and products they sell. Conversely, the export of high value added products from richer countries enables them to produce a higher gross national income to maintain high and import-dependent resource throughputs and inputs. The results stem – at least partly – from underlying differences in labor productivity, which are, in turn, themselves contingent on the unequal availability of technological infrastructure, i.e. industrial technology and machinery (Drucker, 1999; Fischer-Kowalski et al., 2011; Samuelson and Nordhaus, 2005).

The asymmetries in biophysical exchange flows and the disparity in how resource provision is compensated on global markets generate a remarkable phenomenon: In standardized accountings of international trade, money and materials flow in opposite directions (Feenstra, 2015; Odum, 2007). However, when embodied resources are considered, net

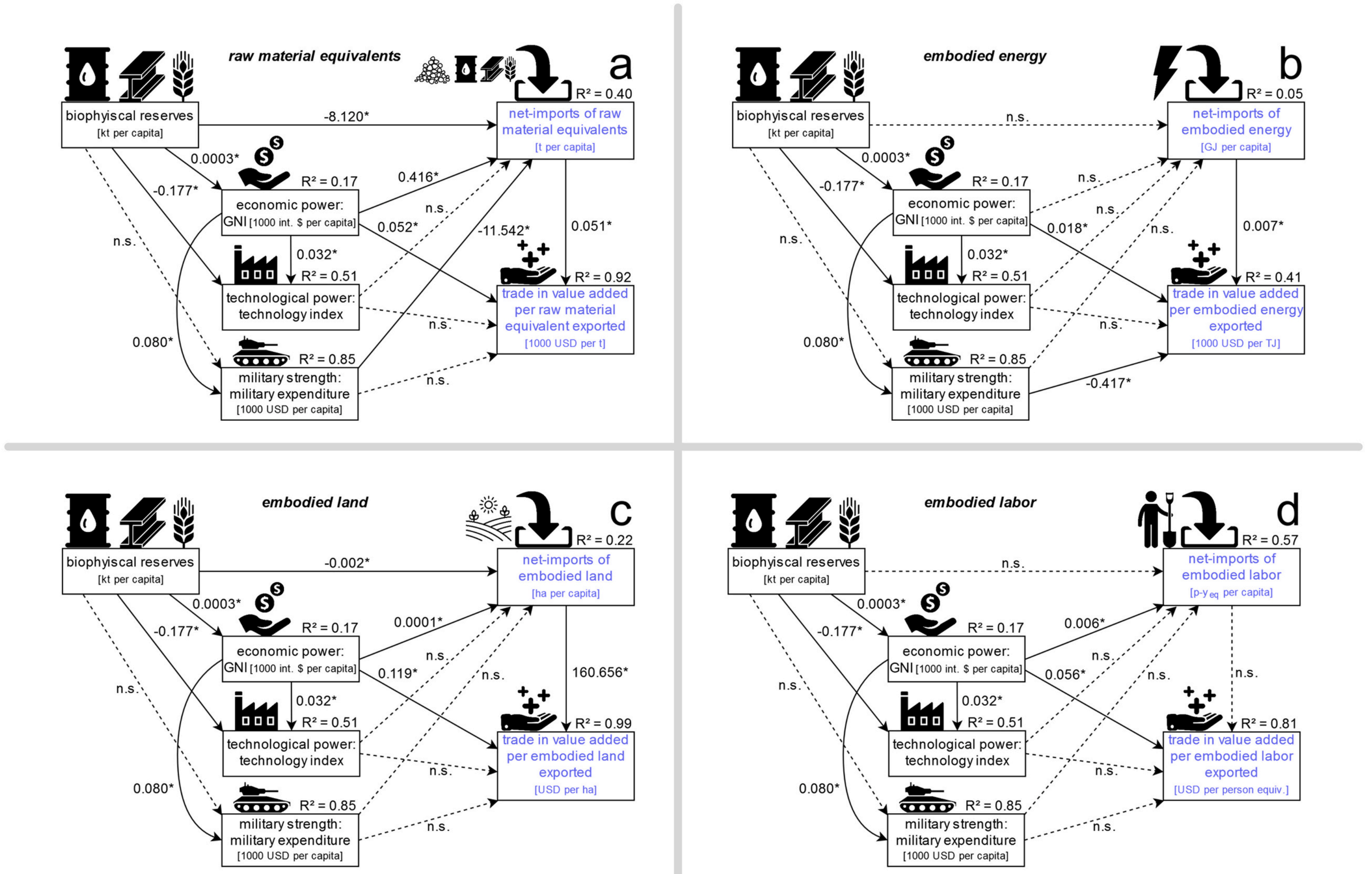

Fig. 4. Piecewise structural equation model quantifying hypothesized relationships between economic and technological power, military strength, biophysical reserves and net imports of resources as well as trade in value added per exported resource item in global trade in 2015 (n = 170). Each of the final SEMs contains 13 relationships, indicated as directed arrows. Path coefficients are not standardized to allow for a direct interpretation of effects in ratios between a rise in the value of the predictor and its effect on the value of the response variable. The four predictor variables on the left of each SEM (reserves, GNI, technology, military) remain unaltered throughout, and only the response variables (net trade and trade in value added) are replaced for each of the four resource types (indicated in blue). The asterisk indicates that the 95% confidence interval around the estimate does not include zero. Non-significant path coefficients are indicated by a dotted line and labeled "n.s.". (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

flows of money and resources are aligned in the same direction. HI nations accomplish a net appropriation of materials, energy, land, and labor, while simultaneously generating a monetary surplus from those net appropriations.

Against the backdrop of the global extent and temporal persistence of ecologically unequal exchange presented in this study, we find that unequal exchange is not coincidental or transitional, but systemic and pervasive in the current structure of the global economy. Its temporal persistence, global validity, and applicability to all four resources assessed underscore its systemic character. And while unequal exchange enables biophysical and economic growth in the benefitting regions, it entails continued inequalities between countries and shifting of environmental burdens to extractive regions (Wiedmann and Lenzen, 2018).

Our findings are consistent with the hypothesis that relationships of ecologically unequal exchange are a prerequisite for the seamless functioning of modern technology (e.g. the automobile industry and its infrastructure, energy production, but also industrial livestock production systems, textiles, or electronics). Therefore, economic growth and technological progress in 'core areas' of the world-system occurs at the expense of the peripheries (Jorgenson and Kick, 2003; Wallerstein, 1974), i.e. growth is fundamentally a matter of appropriation (Hornborg, 2016). In fact, modern technological systems may, in part, be driven by differences in how human time and natural space are compensated in different parts of the world. High resource consumption is enabled by globally prolonged supply chains, favoring countries with high-value added processes (Prell et al., 2014).

Some of the major current sustainability challenges are predictable consequences of ecologically unequal exchange, with particular importance for intra- and inter-generational justice. The manner of industrialization for which the HI countries have provided a blueprint relies on the extraction and processing of fossil energy carriers, metals, and non-metallic minerals in vast amounts. If these resources are not or no longer available within the HI countries, they must be imported from other countries. The problem with this 'strategy' however is that it cannot be pursued indefinitely on a finite planet. High-consumption lifestyles exist at the expense of people elsewhere (thereby creating a question of intragenerational justice) and of future inhabitants of our planet (intergenerational justice). Current trajectories of resource consumption in the high-income nations can neither be sustained indefinitely nor globalized (Cumming and von Cramon-Taubadel, 2018). In the long-run and for the majority of the global population, the often-cited ideal of catch-up development has failed to materialize and needs to be scrutinized much more critically (Duro et al., 2018; Shiva and Mies, 2014). Inequality in consumption and production rests on economic inequality and has a self-reinforcing character.

The scramble for access to resources, such as materials, energy, land, and labor, induced by industrial technologies, fuels economic growth and material wealth in some parts of the world (Cumming and von Cramon-Taubadel, 2018; Gulley et al., 2018). The bigger an economy and its technological infrastructure, the stronger the impact of depreciation and the greater the needs for new inputs to keep it running (Daly, 1991; Smith et al., 2019; Wiedenhofer et al., 2019), to maintain capital and infrastructure. The inequality observed is functional and systematic and not a mere side-effect of growth-led development. To date, the dominant development model has built and depended on these asymmetries and the industrialization it offers as a blueprint cannot become a universal development form.

6. Conclusions

Our analysis highlights how mass consumption and economic growth in high-income countries are sustained by asymmetric exchange relationships with poorer regions. Ecologically unequal exchange rests on and may reinforce economic inequality between countries. The economic growth of wealthier regions is achieved through high mass throughput and concurrent environmental burden shifting to poorer regions. The richest countries in the world tend to be net-appropriators of materials, energy, land, and labor. Being able to generate the world's highest value added and income allows rich nations to appropriate resources in subsequent years, perpetuating unequal exchange relations.

We have shown that the consideration of asymmetric global resource flows is key to understanding how market exchange can obscure inequalities. This fundamental observation is crucial in accounting for the limited political acceptance of the ecologically unequal exchange perspective. What is arguably one of the main sources of inequalities in our modern world is, thereby, kept outside the mainstream field of vision in economics and politics. Thus, policy instruments for mitigating the deleterious global consequences of ecologically unequal exchange are non-existent. Any national attempt that seriously aims at sustainability inevitably must include considerations of ecologically unequal exchange as a structural outcome of the current globalized economic system.

Because the economic growth model of industrialization requires the appropriation of resources from poorer regions, it seems illusory for all poorer nations to be able to 'catch-up' by – among other things – accessing even poorer regions from which to appropriate resources. Industrialization as experienced by the world's wealthiest countries, and some emerging economies like China, cannot become universal. Economic theory must better acknowledge the material aspects of economic flows in order to be able to understand the holistic relationship between economic growth, international trade, and today's global sustainability challenges (Hornborg, 2019).

A common response to the observation that the world economy is characterized by ecologically unequal exchange is: "So what?" For most mainstream economists, the asymmetric global transfers of biophysical resources are a predictable outcome of market structures and the international division of labor. This reaction is noteworthy in two respects. Firstly, it suggests that the exploitative structure of the globalized market is so "naturally" intrinsic to its logic as to be unworthy of consideration. Secondly, it reveals the extent to which mainstream economics has abandoned concerns with the material dimension of its study object. For both these reasons, the empirical phenomenon of ecologically unequal exchange raises crucial *conceptual* issues that can only be given a very cursory treatment here.

To understand the world economy in terms of flows of *value* is conducive to representing the occurrence of economic asymmetries in terms of "underpaid" values, as if market prices only imperfectly correspond to the "real" values of commodities. This approach is fundamental to heterodox schools such as Marxian and ecological economics. However, instead of assuming that commodity flows are to be conceptualized in terms of some purportedly objective measure of *value* (whether based on utility, labor, or energy), we acknowledge that processes of market valuation are social constructions that serve to organize and obscure what can be objectively identified as *materially* unequal exchange. As the material productive potential of a set of commodities is inexorably reduced in the production process (Georgescu-Roegen, 1971), the market will of course tend to value commodities higher the less of the original productive potential that remains. On the other hand, the asymmetric transfers of material resources generated by such market valuation – rewarding resource use with access to more resources – contribute to the concentration of productive infrastructure in core areas of the world economy, which enables these areas to increase their output of high-value commodities. The significance of asymmetric transfers of material resources is thus not that they represent underpaid values, but that they contribute to the physical expansion of productive infrastructure at the receiving end. The accumulation of such technological infrastructure may yield an expanding *output* of economic value, but this is not equivalent to saying that the resources that are embodied in infrastructure have an objective value in excess of their price.

Only by refusing to let our conceptualization of trade be constrained by the concept of "value" can ecologically unequal exchange theory empirically investigate why some extractive zones of the world-system (e.g., Canada, Australia, Scandinavia, Saudi Arabia) have *not* been impoverished by their net exports of resources. Certainly, the existence of historically privileged and sparsely populated nations richly endowed with natural resources has enabled some extractive zones of the world-system to escape impoverishment, but this does not contradict the widespread observation (e.g., Galeano, 1973) that ecologically unequal exchange for centuries has contributed to global polarization and the impoverishment of large segments of the world's population and landscapes. Such polarization, generated by the asymmetric resource transfers we conceptualize as ecologically unequal exchange, can be identified both between and within nations. While we strongly caution against equating productive potential with value, it is incumbent on economic theory to relate global flows of value to the materiality of the world that they produce.

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Declaration of Competing Interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2020.106824.

Appendix B. Appendix

Countries with a GNI per capita (constant international 2011 $ in purchasing power parity; PPP) (World Bank, 2018b) higher than 23,905 $ in 2015 are part of the high-income (HI) cluster (n = 41; 1.14 billion people; 15.5% of world population); countries with a GNI per capita between 10,218 and 23,905 $ are part of the upper-middle income (UMI) cluster (n = 41; 1.19 billion people; 16.1% of world population); countries with per capita incomes between 4956 and 10,128 $ are in the lower-middle income (LMI) cluster (n = 36; 1.15 billion people; 15.7% of world population); and countries with a GNI equal to or below 4956 $ form the low-income (LI) country cluster (n = 50; 1.13 billion people; 15.3% of world population). China (CHN; GNI of 10,288 $; 1.38 billion people; 18.7% of world population) and India (IND, GNI of 5688 $; 1.31 billion people; 17.8% of world population) were treated as distinct cases due to their large populations and significance in terms of international trade.

Fig. 5 also includes boxplots indicating the distribution of material footprint values per capita within the income groups and the significant difference between the groups, which was also confirmed by an ANOVA conducted. Here we can see that the income clusters explain the metabolic rate very well (boxplots etc.).

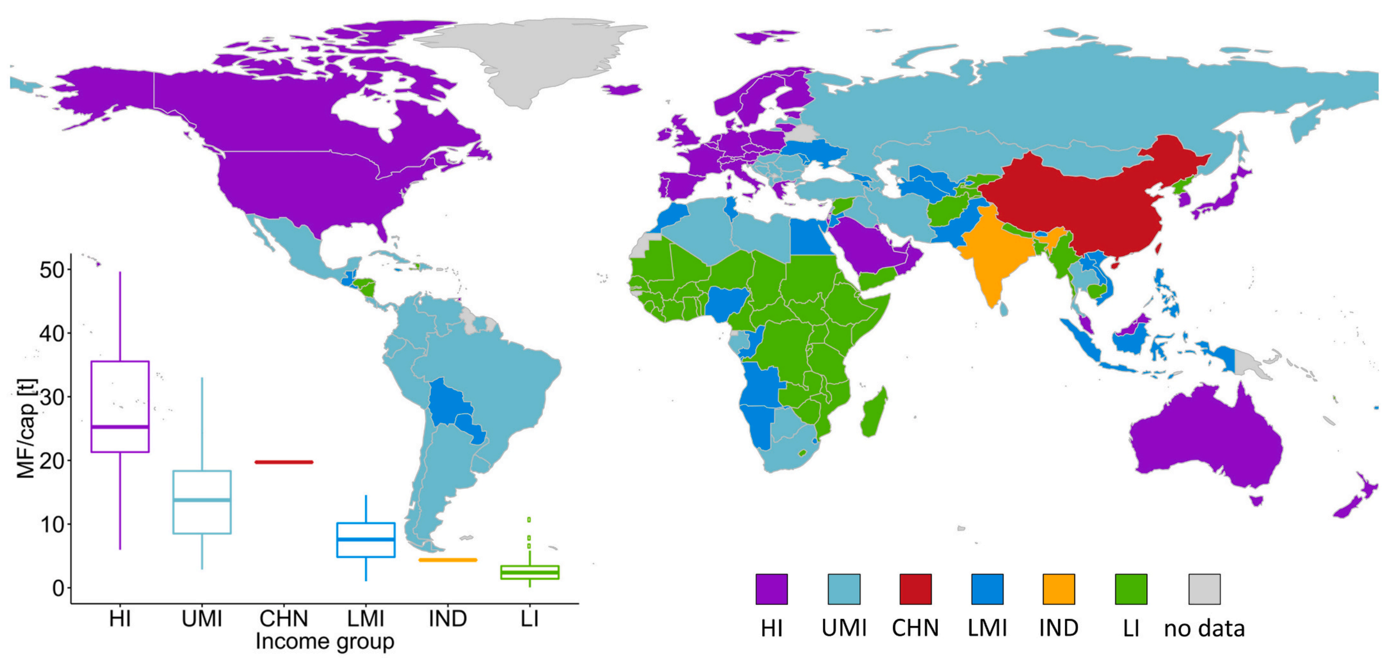

Fig. 5. The global distribution of income clusters in a map and a boxplot of the distribution of the material footprint in each income-group.

Table 1
List of countries.

Low-income (LI)	India (IND)	Lower-middle income (LMI)	China (CHN)	Upper-middle income (UMI)	High-income (HI)
n = 50	*n = 1*	*n = 36*	*n = 1*	*n = 41*	*n = 41*
Afghanistan	India	Albania	China (incl. Taiwan, Macao, and Hong Kong)	Algeria	Australia
Bangladesh		Angola		Antigua	Austria
Benin		Armenia		Argentina	Bahrain
Burkina Faso		Belize		Azerbaijan	Belgium
Burundi		Bhutan		Bahamas	British Virgin Islands
Cambodia		Bolivia		Barbados	Brunei
Cameroon		Bosnia and Herzegovina		Botswana	Canada
Central African Republic		Cape Verde		Brazil	Cyprus
Chad		Congo		Bulgaria	Czech Republic
Cote dIvoire		Ecuador		Chile	Denmark
Djibouti		Egypt		Colombia	Estonia
DR Congo		El Salvador		Costa Rica	Finland
Eritrea		Fiji		Croatia	France
Ethiopia		Georgia		Cuba	Germany
Gambia		Guatemala		Dominican Republic	Iceland
Ghana		Indonesia		Gabon	Ireland
Guinea		Jamaica		Greece	Israel
Haiti		Jordan		Hungary	Italy
Honduras		Maldives		Iran	Japan
Kenya		Moldova		Iraq	Kuwait
Kyrgyzstan		Mongolia		Kazakhstan	Lithuania
Laos		Morocco		Latvia	Luxembourg
Lesotho		Namibia		Lebanon	Malta
Liberia		Nigeria		Libya	Netherlands
Madagascar		Pakistan		Malaysia	New Zealand
Malawi		Paraguay		Mauritius	Norway
Mali		Peru		Mexico	Oman
Mauritania		Philippines		Montenegro	Portugal
Mozambique		Samoa		Panama	Qatar
Myanmar		Sri Lanka		Poland	Saudi Arabia
Nepal		Swaziland		Romania	Singapore
Nicaragua		Tunisia		Russia	Slovakia
Niger		Turkmenistan		Serbia	Slovenia
North Korea		Ukraine		Seychelles	South Korea
Rwanda		Uzbekistan		South Africa	Spain
Sao Tome and Principe		Viet Nam		Suriname	Sweden
Senegal				TFYR Macedonia	Switzerland
Sierra Leone				Thailand	Trinidad and Tobago
Somalia				Turkey	United Arab Emirates
South Sudan				Uruguay	United Kingdom
Sudan				Venezuela	United States of America
Syria					
Tajikistan					
Tanzania					
Togo					
Uganda					
Vanuatu					
Yemen					
Zambia					
Zimbabwe					

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