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Ecologically unequal exchange and uneven development patterns along global value chains ☆

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ABSTRACT

This paper relates participation in global value chains (GVCs) to development patterns and ecologically unequal exchange (EUE). We conduct a principal components analysis and a clustering analysis along six dimensions (GVC participation, GVC value capture, investment, socioeconomic development, domestic environmental impact and international environmental balance) for 133 countries between 1995 and 2015. We find three social, ecological, productive development and GVC insertion patterns: "*curse of GVC marginalization*", "*ecologically perverse upgrading*" and "*reproduction of the core*". While our results confirm the asymmetry in ecological degradation between high-income and low-income economies shown by EUE, it refines and nuances these findings. We argue that environmental asymmetries are driven in large part by differences in how countries articulate within GVCs. Countries with a higher capacity to capture value from GVC participation ("*reproduction of the core*") are able to displace environmental impacts to countries facing a trade-off between upgrading in GVCs and ecological degradation ("*ecologically perverse upgrading*"). Marginalization from GVCs, mitigates the impact of ecologically unequal exchange but constitutes a barrier to socio-economic benefits. Moreover, the lack of diffusion of more ecologically-efficient processes through GVCs has a negative impact on domestic ecological degradation for countries of the "*curse of GVC marginalization*" group.

1. Introduction

While ecological degradation is a global phenomenon, its driving causes and consequences are far from universal. Despite growing recognition that environmental risks and responsibilities are unevenly distributed across the planet, research bridging global political economy and ecological economics remains underdeveloped.

Applied political economy works, particularly those investigating the changing structure of productive relations through global value chains (GVCs), still poorly account for ecological dynamics in capitalist globalization at the macro level. In particular, they have not sufficiently grappled with the extensive material flows that underpin valorization processes at the global scale. Pioneering research mobilizing the concept of ecologically unequal exchange (EUE) has proposed important steps in this direction (Clark and Foster, 2009; Dorninger et al., 2021; Foster and Holleman, 2014; Givens et al., 2019; Hornborg, 2009, 1998; Magalhães et al., 2019; Piñero et al., 2019).

Highlighting the highly differentiated historical and current national responsibilities in the global ecological crisis, EUE emphasizes the asymmetric transfer of material and energy resources from low-income to high-income countries. Importantly, the EUE literature demonstrates the need to move beyond the fetish of price indicators in order to account for the uneven distribution of environmental degradation.

EUE thus provides a necessary starting-point to account for uneven environmental degradation at the world scale. However, it still needs to further engage with how broader structural changes within capitalism - such as globalization, financialization,

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liberalization of trade and capital flows, etc. - might be driving ecological inequalities (Althouse and Svartzman, 2022; Foster and Holleman, 2014, p. 210). Some authors have pointed to GVCs as an important institutional-material dynamic that intensifies environmental degradation in low-income (peripheral) countries and expands the potential for resource appropriation among high-income (core) countries (Duan et al., 2021; Givens et al., 2019; Meng et al., 2018; Rivera-Basques et al., 2021). It is therefore important to empirically investigate the contribution of GVC dynamics to the material asymmetries embedded within global trade and production. This calls for an in-depth engagement with EUE research.

This contribution proposes to relate participation in global value chains (GVCs) to development patterns in the perspective of ecologically unequal exchange. To do so, it constructs a relational perspective that draws on GVC research and insights from the ecologically unequal exchange framework. We distinguish GVC participation – as a key feature of contemporary globalization – from the more general dynamic of international trade (Carballa Smichowski et al., 2021). GVCs can then be understood as a dynamic that is predicated on the drive towards control over production processes under the hegemony of the profit motive. This drive co-evolves within a diverse geography of economico-institutional-ecological contexts, yet results in predictable patterns of social development and environmental degradation that tend to fall along traditional core-periphery lines.

We draw on these theoretical insights and the corresponding methodological developments to explore at the country level the economic, social, and ecological dimensions of a limited set of development patterns in relation to their integration in GVCs. Further, we aim to articulate the inter-country compossibility of these patterns; that is, we highlight their "*structural coupling, co-evolution and mutual complementarities-exclusivities and their impact on differential accumulation at a world scale*" (Jessop, 2014, p. 54).

Empirically, these different patterns are identified via a geometric data analysis for 133 countries in 1995 and 2015. We use data from well-established international databases along six dimensions (GVC participation, GVC value capture, investment, socioeconomic development, domestic environmental impact and international environmental balance). We find three social, ecological, productive development and GVC insertion patterns: "curse of GVC marginalization", "ecologically perverse upgrading" and "reproduction of the core".

While our results confirm the clear asymmetry in ecological degradation between high-income and low-income economies documented by the EUE literature, we also find reasons to nuance some of its findings. We provide evidence that the distribution of environmental impacts is conditioned in large part by institutional changes in the global division of labor, namely GVCs. More specifically, we distinguish between two types of peripheries: one for which integration to GVCs led to positive socioeconomic outcomes at the expense of taking on the core's ecological burden ("*ecologically-perverse upgrading*"); and another one for which the lack of integration to GVCs led to poor socioeconomic outcomes and a negative domestic ecological impact ("*curse of GVC marginalization*").

The rest of the paper is structured as follows: section 2 engages with the contribution of the EUE perspective to the understanding of uneven development and presents our hypotheses. Section 3 lays out our methodology to relate GVCs to EUE and details the data used in our empirical investigation. Section 4 presents and discusses the results of the analysis, focusing particularly on how our paper nuances findings from within EUE. Section 5 concludes and offers opportunities for further investigation.

2. The contribution of ecologically unequal exchange to uneven development

The findings of research on ecological issues in macro GVCs literature is overall ambiguous.[1] On the one hand, techniques, ideas and standards diffusion are considered along with Kuznets curve dynamics as a way to improve ecological conditions. On the other hand, pollution haven patterns and rebound effects are considered to further deteriorate the environment.

By contrast, the theory of ecologically unequal exchange posits that global trade privileges the asymmetric net flow of biophysical resources and labor time from low-income to high-income countries (Dorninger et al., 2021; Hornborg, 2022). According to EUE, different regions occupy distinct positions within a hierarchically organized world-system wherein material inequalities are reinforced through international exchanges. High-income (core) countries are shown to concentrate in high value-added sectors whose environmental impacts are largely hidden through the workings of international trade system. By contrast, low-income (peripheral) countries are said to concentrate in low value-added and extractive sectors, a function for which they are poorly remunerated. This configuration of the World Economy-Ecology is forcefully documented by EUE in relation to development dynamics. However, some ambiguities regarding unequal exchange need to be clarified to approach this issue from a GVCs perspective.

2.1. Polarizing the world economy through ecologically unequal exchange

EUE describes a vicious circle whereby peripheries are driven to export a greater share of embodied resources and labor time in exchange for less resource-intensive imports from the high-income (core) countries. Peripheries therefore suffer the increasing degradation of their home environments, weak access to necessary material and financial resources, and the disintegration of community well-being (Rice, 2007). Moreover, the concentration of extractive, resource- and pollution-intensive production in low-income countries is said to undermine the functioning of natural systems in peripheries, thereby reinforcing inter- and intra-country inequalities (Althouse et al., 2020). Austin (2021) shows that EUE can even contribute to creating conditions for zoonotic diseases to appear in peripheries. As such, EUE is posed as a significant driver of uneven development, in its own right (Bunker, 1985).

In the EUE perspective, global development is a zero-sum game that favors core countries. The core specializes in conceptualization, logistic and marketing services, and final production stages. These activities are generally less tangibles-intensive and have lower ecological impact. Yet, they are rewarded with the greatest portion of global income. According to the EUE literature, high-income countries are therefore capable of preserving domestic environmental quality through their ability to capture global purchasing power. With a greater share of global income, they have enhanced power to use low-income countries as waste sinks or resource pools.

The empirical literature on EUE forcefully demonstrates these profound divisions. In a study of regions classified according to their relative share of world income, Dorninger et al. (2021) found that every region not classified as high-income between 1990 and 2015 served as net providers of raw materials to global production. Moreover, the value-added per ton of exported goods was shown to be eleven times higher in high-income countries than in those with the lowest income. More generally, the literature has shown

[1] See detailed review and references in the discussion in Appendix 1.

that environmental impacts, including emissions (Jorgenson, 2012; Prell and Sun, 2015), water pollution (Shandra et al., 2008), biodiversity loss (Shandra et al., 2009), and deforestation (Jorgenson, 2006) are overwhelmingly concentrated in peripheral zones.[2]

2.2. From unequal exchange to ecologically unequal exchange: similarities, dissimilarities, and complementarities

EUE and unequal economic exchange are both strongly related and deeply different concepts. On the one hand, at the formal level they look very similar: "unequal economic exchange theory postulated the exchange of more labor for less, ecologically unequal exchange theory has as its basis the exchange of more ecological use value (or nature's product) for less" (Foster and Holleman, 2014, p. 205). More broadly, both are concerned with asymmetric relations between core and peripheral countries and with the imperialistic power structures generating these unequal flows of value and/or resources and their consequences for development. On the other hand, these two concepts refer to distinctive realms of reality. Unequal economic exchange explores the anomalies in the determination of exchange-value in the context of trade between core and peripheral countries; EUE explores how environment-related use-values are displaced in an unbalanced manner between geographical entities, driven by trade dynamics.

Economic unequal exchange takes the form of an underpayment of the products exported by the peripheral countries vis-à-vis products exported by core countries. It arises due to overexploitation of labour in peripheral countries and is thus classically defined as "*the exchange of products whose production involves wage differentials greater than those of productivity*" (Amin, 1977, p. 211). Such non-equivalent exchange is not primarily explained by different productive structures but rather - depending on the authors - by restrictions to labor mobility, monopolistic market structure and/or (geo)political power constitutive of an imperialist order (Braun et al., 1984; Emmanuel, 1972; Mandel, 1975, pp. 343–376; Marini, 2022; Wallerstein, 1995, pp. 31–33). Economic unequal exchange provides a rent to metropoles that contributes cumulatively to uneven development in the capitalist world economy and reinforces power discrepancies between different poles of the world system (Cope, 2019; Hickel et al., 2022, 2021; Smith, 2016). It is constitutive of imperialism defined as "the system of an unequal, hierarchical world economy, dominated by giant monopolistic corporations and a handful of states in the imperial core" (Suwandi, 2019, p. 152).

In contrast to unequal economic exchange, EUE looks at the metabolic rift between the localization of the depredation of ecosystems resulting from human activities and the enjoyment of the consumption of the use value which finds its source as "free gift of nature" (Marx, 1894, chap. 44). Moreover, EUE cannot conceivably be reduced to a single quantitative indicator since species, ecosystems and geological resources are ontologically incommensurable.

This ontological issue of incommensurability is a fundamental challenge to the empirical exploration of EUE: the ultimate losses in terms of real wealth for given places cannot be fully captured because it is essentially a matter of quality (Foster and Clark, 2009; Marx, 1867, pp. 133–134). However, rather than looking at local impacts, empirical EUE research is mainly attentive to multidimensional resource imbalances in international trade as the manifestation of ecological injustice (Givens et al., 2019). Those can be effectively captured through various dimensions (labour time, energy, biodiversity, matters, GHG emissions..) that can be reasonably well evaluated or estimated by currently available data (see Section 2.1.). This allows to map out the international social metabolism, its uneven spatial distribution and the resulting international ecological inequalities.

Recent empirical research about EUE (section 2.1) is inspired by what Hornborg terms the non-reductionist school of ecological economics (2014). Such a perspective denies the very possibility of an ecologically *equal* exchange due to the uneven accumulation of technologies. Accordingly, technologies are then necessarily supported by uneven material and energy flows. The very existence of a given technology demands that lower-value, lower-entropy inputs are transformed to produce higher-value, higher-entropy outputs. Technologies are therefore considered to be an index of global purchasing power which necessarily drive unsustainable outcomes. Hornborg (2016), for example, writes that when viewing technology through the lens of international transfers:

"*Modern technology is always and everywhere a matter of uneven distribution in global society. This means that the extent to which a given technology is adopted hinges on the distribution of money in the world-system, and that the technology itself represents an unequal exchange of resources between different economic segments of global society.*" (Hornborg, 2016, p. 115).

In other words, as soon as any technological progress anywhere on earth has repercussions on trade flows, these flows become more asymmetrical in terms of embodied natural space. EUE is said to occur, by definition, since more sophisticated products have lower remaining productive potential (higher entropy) than less sophisticated products and the productive potential of any good is inversely related to the price (Hornborg, 2022, 2014). Following this argument, balanced exchanges in monetary terms between technologically unequal countries necessarily require unbalanced physical exchanges. Consequently, the development of international trade entails a process of accentuated depredation of ecosystems located in less technologically sophisticated economies.

Although relying on a different ontology than unequal economic exchange, EUE complementarily reinforces the argument of the former concerning the polarisation of the world economy. According to the unequal economic exchange perspective, core countries can obtain more value from trade than other countries (the periphery). This contributes to uneven development, which reinforces technological asymmetries. According to the EUE, countries with more productive and capital-intensive technologies benefit from unequal material and energy flows when trading with other countries, to the detriment of countries in the periphery. Technological asymmetries then create self-reinforcing socio-economic and ecological asymmetries between core and periphery, as documented in the uneven development and EUE literatures (see amongst others Austin, 2021; Dorninger et al., 2021; Dorninger and Hornborg, 2015; Foster and Holleman, 2014; Givens and Huang, 2021; Hao, 2020; Henriques and Böhm, 2022; Hornborg and Martinez-Alier, 2016; Infante-Amate and Krausmann, 2019; Jorgenson et al., 2009; Prell and Sun, 2015).

Distinctively but complementarily to unequal economic exchange, EUE is thus the mediating mechanism between the hierarchical structure of the world economy, the uneven ecological degradation of the planet and under-development in peripheral countries.

2.3. Ecologically unequal exchange beyond net flows

Nevertheless, the impact of technological progress on EUE and overall ecological degradation is not always straightforward as shown by Table 1.

By standard accounting definitions of EUE (Dorninger et al., 2021; Moran et al., 2013; Rivera-Basques et al., 2021), everything

[2] See Torras (2003) for an economic quantification of the "ecological debt" generated by the uneven distribution of environmental impacts to the detriment of the peripheries.

Table 1
Beyond ecologically unequal exchange: the compossibility of perverse and virtuous dynamic of economic-ecological regimes.

	Global Footprint	Core domestic impact	Periphery domestic impact	Unequal Exchange
Offshoring	+	–	+	+
Reshoring	–	+	–	–
Efficiency core	–	–	=	+
Efficiency periphery	–	=	–	–

being equal, increasing offshoring from core regions to the periphery will lead to greater unequal exchange and higher global footprint, while reshoring will foster less unequal exchange and reduce the global footprint. Alternatively, everything else being equal, a reduction in the use of environmental inputs and the generation of environmental wastes (i.e. increased environmental efficiency) in the periphery would also both reduce unequal exchange and the global footprint.

However, the dynamic is less straightforward when one considers the impact of greater efficiency in the use of resources in core countries. More efficiency may increase EUE, if one only considers net-trade results, at the same time as it helps economizing on planetary resource use, assuming any rebound effect is smaller than efficiency gains. Focusing on net flows, the effect of different levels of efficiency and the effect of progressive technological changes are difficult to disentangle in the aggregate statistics accounting for embodied material and energy flows (Duan et al., 2021).

For example, all else equal, increases in domestic environmental efficiency in a high-income country result in a *reduction of ecological degradation embodied in exports* which leads to an increased ecological imbalance. Such an improvements in ecological efficiency by a high-income country would appear as an increase in ecologically unequal exchange (EUE) that could be mis-attributed to greater environmental load displacement (see the Pollution Haven Hypothesis in Appendix 1).[3] For this reason, Jiborn et al. (2018) propose a more demanding definition of EUE than the mere exchange of more embodied energy for less: studies would have to show both (i) that there is a reduction in domestic environmental impacts through trade and (ii) this reduction is linked to rising environmental impacts elsewhere, compared to a no-trade scenario.

This disambiguation does not imply that low-income countries are responsible for being less efficient than high-income countries, nor that an increase in efficiency in the former can constitute a solution to the structural character of EUE resulting from an uneven geographical distribution of the "technomass" (Hornborg, 2016, p. 33). Moreover, standard EUE accounting can technically differentiate between an increase in efficiency gains in the core (implying less resources embodied in exports from the core) and higher environment load displacement to the periphery (implying increased imports to the core) by simply analysing the evolution of gross material flows.

In order to accurately interpret changes in international ecological dynamics, it is thus important to be able to distinguish between environmental load displacement between countries and increased domestic environmental efficiency.[4] To highlight such distinct mechanisms, research must look beyond pure exchange relations to grasp virtuous and perverse developmental and ecological dynamics in different regions. As Malm (2012) has noted, EUE theory cannot fully capture the systemic dynamics of globalization's metabolism without appealing to the organization of production, since environmental degradation cannot be reduced to bilateral resource exchanges, alone.

If the global distribution of environmental pressures cannot completely be related to technology or formal exchange, there is room for an approach that considers the role of GVCs as a form of industrial organization in the unfolding of EUE.

2.4. Hypotheses

Technological asymmetries between countries generate self-reinforcing socio-economic and ecological asymmetries between the Global North and the Global South that operate and manifest through trade. A central feature of contemporary trade is that it increasingly takes the form of GVCs, which are a major arena where (technologically-driven) power asymmetries between countries may evolve (through so-called "upgrading" and "downgrading" dynamics), resulting in changes in developmental and ecological asymmetries (Baglioni and Campling, 2017; Piñero et al., 2019).

GVCs arise as a new form of industrial organization due to "the second unbundling": "*As the ICT revolution lowered the cost of coordinating complex processes across great distances (...) it [became] possible to separate manufacturing processes internationally*" (Baldwin, 2016, p. 109). Firms with sufficient resources took advantage of this new ability to circulate knowledge and information to project their control capacities over labor processes internationally. To minimize their costs and sustain their profitability, they offshore labor-intensive stages of production from high-wage nations to low-wage nations, shift the location of activities as a result of regulatory or fiscal arbitrage, and deploy global sourcing strategies to benefit from the opportunities offered by the expansion of their potential supply base.

In this context, GVCs cannot be conceptualized simply as a new form of trade characterized by increased international fragmentation. What is at stake is a form of international projection of production processes to variegated economico-institutional contexts under the hegemony of the profit motive. A GVC should then be thought of as "*an institutional and economic production and valorization space where one (or a small number of) lead actor(s) exert(s) economic power to (partially) centralize profits and control(s) to some degree the labor process over geographically and often legally dispersed productive units.*" (Carballa Smichowski et al., 2021, p. 275). In such a perspective, the trade of commodities such as primary products should not be considered as GVC trade. Indeed, they tend to be governed by market dynamics more than by de *facto control* on labour process and technologies, which is the case in many manufacturing and service value chains.

In keeping with this definition, we explore in this paper the ecological consequences of participation in GVCs and the resulting articulation of development patterns. We examine empirically how different levels of country-level GVC participation and value capture relate to ecological and socio-economic asymmetries

[3] According to Kander et al (2015), this situation can even hold when a highly energy-efficient country specializes in exporting more energy-intensive production than what it imports. While such an exchange would reduce aggregate global emissions, as well as the emissions of the trading partner, aggregate accounting methods are likely to label this as an increase in EUE.

[4] Of course, the hypothetical efficiency gains are relevant for the discussion here only "everything else being equal", i.e., without changes in structural composition of the economy. As rightly pointed out by an anonymous reviewer, if a country increases its overall environmental efficiency by specializing in cleaner sectors, then the increases in the imbalances correspond to an effective increased displacement of environmental load, since it will have to import polluting products that it used to produce on its own territory. Looking into those dynamics at the sectoral level is not possible within the limits of this article but it would represent an important development.

between countries. Specifically, we hypothesize that the economic, political and broader institutional dimensions of GVCs make them a driver of the self-reinforcing socio-economic and ecological asymmetries.

However, our empirical exercise is designed in such a way that it does not exclude the possibility of capturing the inverse dynamic posited by some literature (OECD, 2021; World Bank, 2020, pp. 118–131): a *rosy scenario* in which GVCs promote virtuous development patterns for all while simultaneously reducing the global ecological burden (see Appendix 1).

In contrast to this rosy scenario, we expect to find complex relational patterns of development and ecological impact associated with GVC trade. The conceptual framework we advance to understand this articulation is represented in Fig. 1. It underscores the relational dimension of development patterns associated with increasing (decreasing) participation in GVCs in the core and the periphery. Moreover, it proposes three main hypotheses considering the socio-economic, productive, and ecological consequences of GVC participation.

2.4.1. H1. Negative productive effect of GVC participation in core countries, but positive effect in the periphery

Increased (decreased) participation in GVCs is adverse (favourable) to productive expansion for core countries as for them increased (decreased) participation in GVCs mostly means offshoring (reshoring) physical production activities.

For peripheral countries, increased participation in GVCs has a positive effect on productive dynamics as the expansion of foreign demand incentivizes investment. However, the lack of ability to capture value and the lack of internal articulation can nurture a process of immiserizing growth (Kaplinsky, 2004, 2000; Knauss, 2019; Milberg and Houston, 2005) consistent with poor economic achievements in spite of increased productive sophistication. A retreat of globalization could have the same effect in reverse, in terms of lower demand outlets but improved perspective of internal articulation and value capture.

2.4.2. H2: Diversity of socioeconomic effects of GVC participation

Increased (decreased) GVC participation allows for a variety of socioeconomic outcomes both in core countries and peripheral countries, depending on the domestic institutional settings and internal balance of social forces. We are inclined to consider that *divide and rule* dynamics should diminish the associational power of labor (Peoples and Sugden, 2000; Wright, 2000). The pressure on wages and labor standards of a *global reserve army* of labour should negatively affect socioeconomic outcomes. However, these factors could be counterbalanced by the distribution of some of the value capture by corporations in core countries, by productive dynamics in the periphery, and by diverse national institutional configurations.

2.4.3. H3. Negative global ecological impacts of GVC participation with some relative gains to the core at the expense of the periphery

In terms of ecological impact, we hypothesize that GVC participation always has a negative impact at the global level, largely since processes performed in the periphery are dirtier than in the core. First, this is likely because peripheral infrastructure and manufacturing processes have lower energy and resource efficiency and therefore tend to rely more on fossil fuels (Jiang and Green, 2017). Second, GVC participation also fosters ecologically unequal exchange, implying the displacement of the ecological burden at the expense of the periphery and to the benefit of the core. The most polluting and environmentally intensive production processes are likely to be offshored to the periphery.

Conversely, a retreat from globalization should be beneficial to the environment as some productive activities are reshored to places with cleaner and less resources intensive productive processes in the core, which should also reduce the material imbalances of trade vis-à-vis the periphery.

However, as shown in Table 1, these relational dynamics could be affected by potential ecological improvement in productive processes in the core. Provided that their positive global ecological impact is larger than the negative ecological effect of offshoring, we could observe a decrease in overall ecological impact and an increase in core-periphery material imbalances, simultaneously.

3. Data analytics

The aim of this contribution is to show the diversity of development patterns and ecologically unequal exchange dynamics in relation to participation in GVCs. As cross-national macro regressions risk masking the heterogeneity of relationships among the variables by sub-groups of countries (Rodriguez and Rodrik, 2000), we perform a principal component analysis (PCA) and then a cluster analysis. This methodology is suited to capture the heterogeneity of relationships between economic, social, and ecological variables among groups of countries.

3.1. Construction of variables and data sources

Our analysis includes six dimensions at the country level: participation in GVCs, value capture in GVCs, productive development, socio-economic development, domestic ecological impact, and the external balance of ecological degradation. The first two dimensions of participation and value capture in GVCs rely on Carballa-Smichowski et al. (2021).

To evaluate productive development, we selected a country's investment rate and capital stock as our variables. For the socio-economic development dimension, four variables capture the multi-dimensional nature of 'social upgrading' (Milberg and Winkler, 2013, p. 251): the rate of employment, the Palma ratio of inequality, the median income and labour's share of income.

Environmental variables include measures for biodiversity loss, material extraction, local pollutants, and CO2 emissions. These variables account for the main aspects of the ecological footprint of economic activities. We approach countries' ecological footprint in two ways, reflecting our two ecological dimensions. First, we measure environmental impacts domestically, through production-based environmental variables. Second, we include an international environmental balance – a consumption-based perspective – which accounts for the environmental content embodied in net imports (Peters, 2008; Piñero et al., 2019). As such, we include a total of 8 ecological variables.

We collected data for 133 countries for these 16 variables for the years 1995 and 2015. While some variables (e.g., the employment rate) were retrieved from a single source, others (e.g., GVC participation) were built using multiple sources. Table 2 lists all variables and the data sources employed to retrieve or build them. Appendix 2 details how these data were compiled and their limitations.

To build our six dimension-based indexes and proceed to the statistical analysis, we proceed to a z-score normalization. We center all variables around a mean of 0 and normalize them by the standard deviation. Our objective is to assess the *evolution* of development patterns and ecological dynamics along with insertion in GVCs: we opt for a hybrid treatment that considers both the differences in initial levels in 1995 and the differences in variation between 1995 and 2015. The reason for this is that the variation rate alone is not sufficient to meaningfully assess the relative shift in countries' positioning given large differences in initial levels. Based on our normalized raw variables we compose an index for

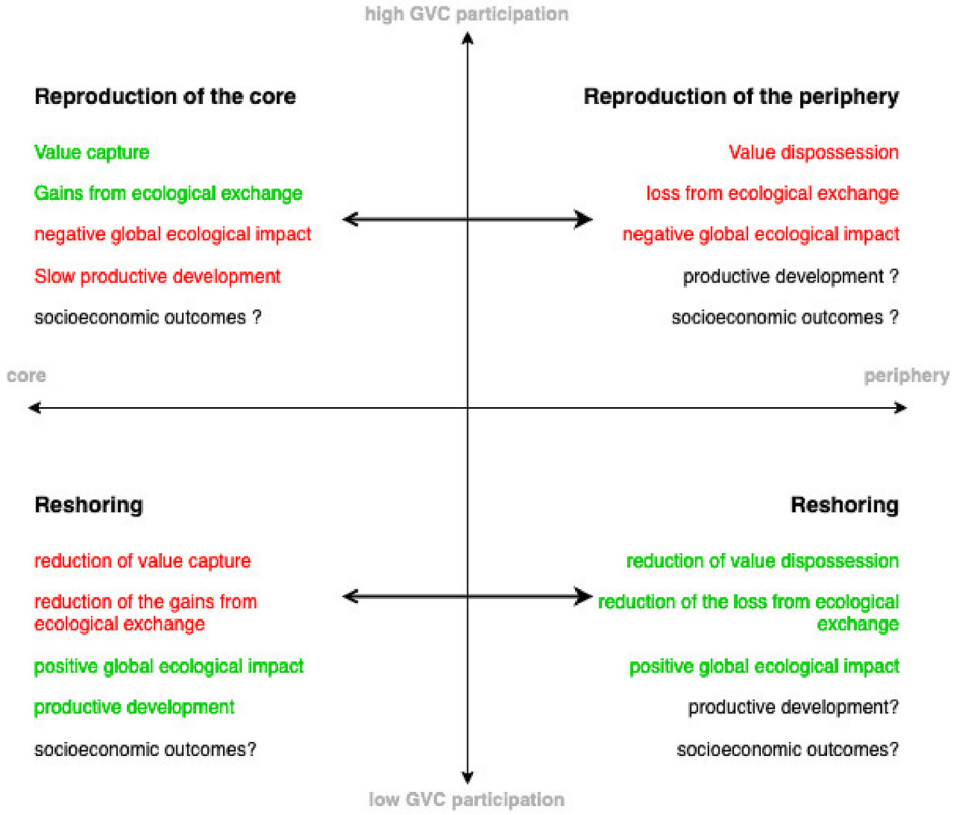

Fig. 1. Ecological and socioeconomic compossibility of development patterns along GVCs.

the six dimensions used in our analysis (see Table 2). We weigh each raw variable within that dimension equally. For each variable, we weigh the 1995–2015 evolution and the initial 1995 value equally (details are provided in the Appendix 2).

With the resulting indexes, we run our PCA for 133 countries for the period from 1995 to 2015. We then use the results to perform a cluster analysis that leads to the identification of three groups of countries. These groups represent three GVC-related patterns of development and ecologically unequal exchange (Section 3.3).

3.2. Statistical analysis

The principal component analysis is therefore performed with six index variables for 133 countries. For the two GVC dimensions – GVC participation and GVC value capture – a higher score indicates a greater gain in GVC participation and value capture between 1995 and 2015 and/or higher initial levels of GVC participation and value capture within GVCs in 1995. The interpretation of the other four dimensions follows the same logic. A higher productive development index indicates greater gains and/or initial levels in investment rates and/or capital stock. A higher socioeconomic score indicates greater gains (and/or initial levels) toward outcomes associated with social upgrading along the four underlying variables: a more equal society as measured by the labour share of income and the Palma ratio; a better standard of living as measured by a higher median income and employment rate.

A higher score for domestic ecological impact represents bigger increases in domestic pollution (CO2 and/or other local pollutants), biodiversity loss and/or material extraction (and/or higher initial levels in 1995). A higher score for the net external balance of ecological degradation indicates that the amount of pollution (CO2 and/or other local pollutants), biodiversity loss, and/or material extraction carried out abroad to satisfy a country's final demand grew more rapidly than a country's domestic ecological impacts embedded in exports to foreign countries (and/or was already much higher initially in 1995). In other words, it can be seen as a measure of ecologically unequal exchange as it is often measured in the literature.

Before performing our statistical analysis, we check whether our data are suited for factor analysis using the Keyser-Meyer-Ohlin (KMO) and Bartlett tests (see Appendix 2). We then analyse our dataset made of the six index variables using a principal component analysis and a hierarchical clustering. Performing the PCA before the clustering reduces the number of dimensions to be analysed: it gets rid of the noise in the data and keeps only the statistically significant information. It therefore improves the quality and the stability of the clustering, which we perform on the principal components rather than on the raw data (Husson et al., 2017, Husson et al., 2010).[5]

Our analysis indicates that at a 90% confidence level the first axis is statistically significant and carries real information. This axis presents an amount of inertia of 33.02%. This is higher than the reference value of 23.11%, which is the 0.9-quantile of the inertia percentages distribution obtained by simulating 100,000 normally distributed data tables of equivalent size. We further apply the usual Keiser criterion of selecting axes with an eigenvalue greater than 1, leading to keep three axes. This criterion has some issues, as it carries the risk of under-estimating or over-estimating the number of components to select (Mulaik, 2010). However, combined with the computation of the statistical significance of our axes, we think it is reasonable to keep the first three principal components: this allows us to keep 67.9% of the total inertia while

[5] See the Appendix 2 for alternative strategies.

Table 2
Description of the variables and the data sources.

Dimension	Variable	Meaning	Description	Data sources
GVC insertion	GVCpart	GVC participation	GVC trade* as percentage of GDP	Eora26 (trade), World Bank (GDP), UNCTADStat (share of primary products in trade)
	GVCvalcap	GVC value capture	Value captured from GVC trade as a percentage of GVC trade	
Productive development	invrate	Investment rate	Gross fixed investment as percentage of GDP	World Economic Outlook (IMF)
	Kstockpop	Capital stock	Capital stock (constant 2017 USD PPP) per capita	Penn World Tables (capital stock in current USD 2017 PPP), World Bank (population and deflator)
Socio-economic development	emprate	Employment rate	Employed population as a share of active population	ILOStat
	invpalma	Palma ratio	Top 10% share of income as a ratio of bottom 40% share of income	World Inequality Database (WID)
	medinc	Median Income	Median income (household per capita equivalized, 2014 USD PPP)	PovcalNet (World Bank)
	labshare	Labor share	Gross wages as a share of net value added	Eora26
Domestic ecological impact	biodiv_ctrsize	Biodiversity loss	Domestic biodiversity loss normalized by country size. Biodiversity loss is measured as potentially disappeared fraction of species	Bjelle et al. (2021), World Bank (country size)
	domextract_ctrsize	Domestic material extraction	Domestic material extraction normalized by country size	UNEP Global Material Flows Database (materials), World Bank (country size)
	locpollgdp	Local pollutants	Kilograms of domestic local pollutant emissions per 2017$ PPP GDP	Edgar v5 (pollutants), World Bank WDI (GDP)
	co2gdp	CO2 emissions	Kilograms of domestic CO2 emissions per 2017$ PPP GDP	World Bank WDI
External balance of ecological degradation	rawtb_matfoot	Raw materials trade balance	Net embodied imports of materials as % of material footprint	UNEP Global Material Flows Database
	biodiv_importfoot	Biodiversity loss imports	Net embodied imports of biodiversity loss as % of biodiversity footprint	Bjelle et al. (2021)
	locpoll_importfoot	Local pollutant imports	Net embodied imports of local pollutants as % of local pollutant footprint	EDGAR v5, Eora, World Bank
	co2impfoot	CO2 imports	Net embodied imports of CO2 as % of CO2 footprint	Eora

*As defined by Carballa Smichowski, Durand & Knauss (2021).

still removing a substantial amount of the statistical noise contained in the data.[6]

3.3. Results of cluster analysis

Table 3 shows the country composition of each class resulting from the cluster analysis along with the number of countries in each grouping. To understand the specific features of these three country classes, we now turn to their intrinsic characteristics.[7] We proceed by calculating the mean value of the six synthetic indexes used in the PCA for each class and we compare them to the sample mean. The rationale for this method is simple: when the mean of one of the indexes for a class is significantly higher/lower than the mean of all countries in the sample, we can say that a high/low value of that index is characteristic of the class, relative to the whole sample. Given that the raw variables were standardized to build the indexes, the mean of the sample is equal to 0 for each index.

Fig. 2 shows the result of these calculations in a radial graph. At the end of the section, Fig. 3 provides a 3D representation of the cluster groupings. It allows for a direct appreciation of countries' positions along the three retained axes of the PCA. Tables 4, 5, and 6 summarize the median initial 1995 values, median 1995–2015 variation rates, and the median final 2015 values for all underlying raw variables by cluster and for the whole sample. Table 7 reports the absolute amount of domestic environmental impact by cluster, for 1995 and in terms of 1995–2015 evolution.

3.3.1. Cluster 1

Relative to the rest of the sample, cluster 1 is characterized by a low GVC participation and value capture. These countries are less integrated in GVCs than other countries, and their participation even declines in absolute terms over the course of the period (Table 5). They exhibit low productive development, poor socio-economic outcomes, and high domestic ecological degradation. The external ecological balance of cluster 1 is not significantly different from the sample average.

The external ecological balance is at first glance puzzling, as one would expect these countries to exhibit a negative balance – that is, to be net exporters of embedded raw materials, pollution, and biodiversity loss. Indeed, the weak integration in GVCs suggests that these countries export raw materials or basic products to pay for their imports of final products. Since raw materials and

[6] All the analyses were performed using the packages FactomineR, FactoInvestigate and missMDA for R (Husson et al., 2020; Husson and Thuleau, 2020; Josse and Husson, 2016).

[7] The reader should bear in mind three things when analysing the country composition of the clusters. First, the interpretation of a cluster's characteristics is not valid at the level of each observation (country), but rather at the level of the cluster itself. We follow this interpretation in the following lines. Second, the country composition of a cluster in which countries are the observations is robust if a large majority of them are similar with respect to the variables and timeframe used. This is the case in our three clusters. However, this does not exclude the possibility that observations (countries) belonging to the same cluster be highly dissimilar with regards to other variables not included in the analysis. Third, while increasing the number of clusters necessarily reduces the heterogeneity between the observations (countries) that compose them, it also diminishes their capacity to generate meaningful groupings. In the extreme, each observation (country) is itself its best cluster. To navigate this trade-off, as explained in Section 3.2 of Appendix 2, we opted for a hierarchical clustering method.

Table 3
Country composition of the clusters.

Clusters	Cluster 1	Cluster 2	Cluster 3
Composition	Albania, Armenia, Azerbaijan, Burundi, Bahrain, Bahamas, Bosnia & Herzegovina, Belize, Bolivia, Botswana, Central African Republic, Chile, Côte d'Ivoire, Cameroon, Congo - Kinshasa, Colombia, Cape Verde, Costa Rica, Cyprus, Dominican Republic, Ecuador, Egypt, Ghana, Gambia, Greece, Guatemala, Honduras, India, Jamaica, Kazakhstan, Kenya, Kuwait, Lebanon, Lesotho, Madagascar, Mali, Mongolia, Mozambique, Mauritania, Mauritius, Malawi, Namibia, Niger, Nigeria, Nicaragua, Nepal, Peru, Paraguay, Rwanda, Saudi Arabia, Senegal, Sierra Leone, Eswatini, Chad, Togo, Tajikistan, Turkmenistan, Tanzania, Uruguay, South Africa, Zambia	Angola, Argentina, Australia, Bangladesh, Bulgaria, Brazil, Brunei, Bhutan, China, Algeria, Gabon, Georgia, Croatia, Indonesia, Iran, Cambodia, Sri Lanka, Morocco, Mexico, North Macedonia, Malaysia, Oman, Pakistan, Philippines, Poland, Romania, Russia, Thailand, Tunisia, Uganda, Ukraine, Uzbekistan, Vietnam	United Arab Emirates, Austria, Belgium, Canada, Switzerland, Czechia, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom, Hungary, Ireland, Iceland, Israel, Italy, Jordan, Japan, Kyrgyzstan, South Korea, Lithuania, Luxembourg, Latvia, Maldives, Malta, Netherlands, Norway, New Zealand, Panama, Portugal, Singapore, El Salvador, Slovakia, Slovenia, Sweden, Turkey, United States
Total	61	33	39

basic products tend to use ecological resources more intensively than the manufactured goods that represent the bulk of final products, the cluster should have a negative external ecological balance.

This result requires two important qualifications. First, Table 4 shows that at the initial 1995 level, the two positive variables in the overall ecological balance index are the local pollutant external balance and the CO2 external balance. One way of interpreting this result is that the positive balance could simply stem from a lack of industrial development and a more extensive use of human and animal labour. This would allow for a less intensive use of chemicals and other mechanical processes in their exports than in the products they import. This is consistent with Prell and Sun (2015) who find a U-shaped relation between net carbon imports and GDP per capita: least and most developed countries are net importers of CO2 while middle income countries tend to be net exporters. As discussed below about clusters 2 and 3, our results confirm this U-shaped relation, at least for some environmental variables like CO2.

This qualification is particularly important: *(i)* the two other dimensions of the external ecological balance have negative initial values (materials balance and biodiversity balance); *(ii)* for the four variables (Table 5), the evolution of the balances is negative, indicating an overall degradation between 1995 and 2015 of the overall position. This is the only cluster to experience a negative evolution of its materials external balance, which points to an overall increase in environmental degradation through exports.

Fig. 3 helps to further characterize cluster 1. Although all three retained axes of the PCA are statistically significant, axis 1 is the most significant, and cluster 1 countries have mostly negative values on axis 1. This indicates notably low values for GVC participation and value capture, and a high value for domestic ecological impact, which are the three PCA variables most strongly determining this axis. However, other variables are also significant to determine this axis (see details of the PCA results in Appendix 2). Marginalization from the 'benefits' of participating in global value chains and high domestic ecological degradation are thus the main features of this cluster.

3.3.2. Cluster 2

As can be seen in Fig. 2, the dynamics of GVC participation and value capture for cluster 2 are not significantly different than the sample average. Cluster 2 has the best outcome in terms of productive development, along with an improving socio-economic development. In terms of ecological outcomes, however, this class faces the worst dynamics. Countries in cluster 2 have both a high ecological domestic degradation and a degradation of their external ecological balance.

Tables 4, 5 and 6 help to specify the dynamic at stake. Continuity in GVC integration and value capture can be related to median income growth, reduced inequalities, and productive development. Capital stock per capita at the initial 1995 level was larger than in cluster 1 and it continued to expand with high investment levels. However, these positive developments came along with an accelerated degradation of the external ecological balance in three of the four variables underlying this dimension.

Fig. 3 shows that cluster 2 is primarily determined by axis 2. Most of the countries in this cluster have positive values on axis 2. This indicates high values for productive and socio-economic development and a low value for the external ecological balance.

Overall, countries from cluster 2 managed to maintain their GVC integration and value capture, yet at high environmental cost. Cluster 2 appears to have fuelled their productive development and enhanced socio-economic variables in large part by exploiting domestic natural resources. This domestic exploitation was thus linked to their specific articulation within GVCs, as implied by their negative external ecological balance.

3.3.3. Cluster 3

Fig. 2 shows that cluster 3 is characterized by intense participation and value capture in GVCs. Productive development is high and socioeconomic development is more favourable than in the rest of the sample. Ecological degradation, in turn, is relatively more reduced domestically while the countries benefit from a favourable external ecological balance (i.e., they offshore their ecological impact abroad). This position is corroborated by initial values and variation rates exhibited in Table 4 and Table 5. It is also worth noticing that, contrary to other clusters, this cluster experienced a negative evolution of the labour share and a growth in inequality, as indicated by the inverse Palma ratio. As such, the overall high positioning in terms of socioeconomic outcomes reflects a favourable initial position rather than an improvement. Also worth noting, the employment rate of cluster 3 was the lowest in 1995 and grew the most over the period.

Cluster 3 is mostly determined by axis 1. Interestingly, axis 3 is not significant to determine this cluster. This explains what can be, at first sight, puzzling when looking at Fig. 3. Indeed, we can see that as far as axis 3 is concerned, countries of the core seem to be on the low side of GVC participation and value capture. This is not the case, as clearly indicated by axis 1. Almost all these countries have positive coordinate on this axis, indicating positive val-

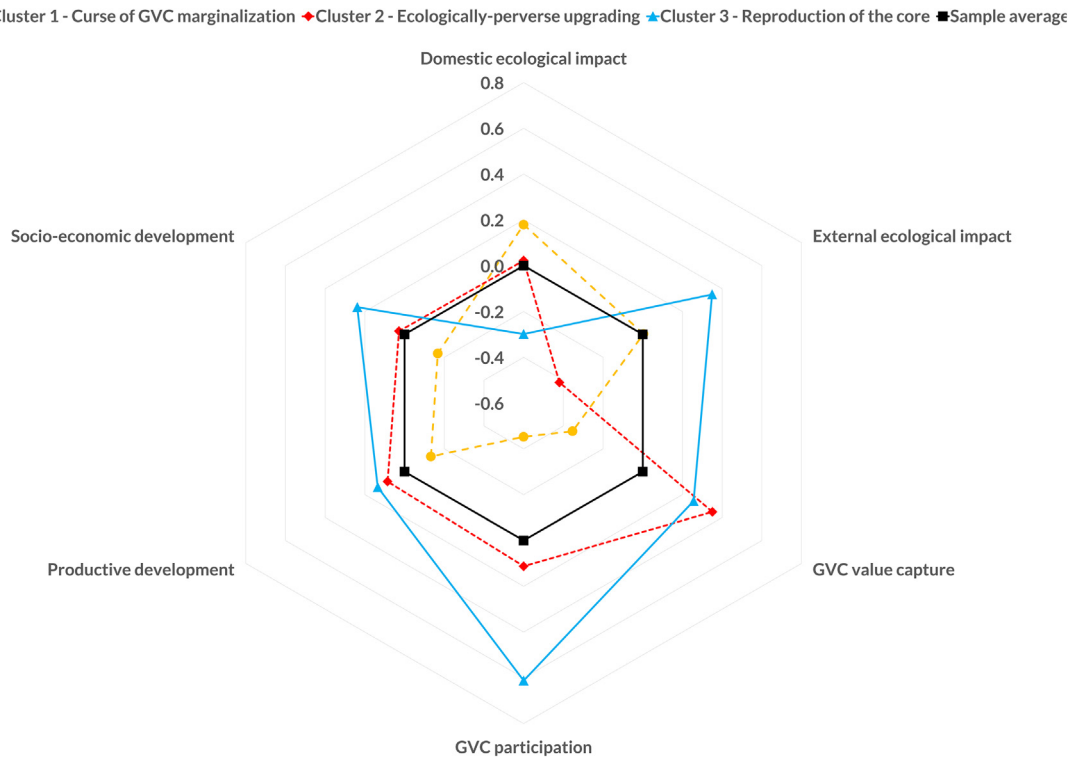

Fig. 2. Mean value of each variable by class and for the sample as a whole.

ues for GVC variables and lower values for domestic ecological impact.

4. Discussion

This section briefly discusses our results. After presenting the three compossible development patterns that can be identified (Table 8), we elaborate on the implications of this analysis for the ecologically unequal exchange perspective and our understating of the GVC-environment nexus.

4.1. Labelling three compossible development patterns

Cluster 1, which we label ***the curse of GVC marginalization***, is made up of countries that stayed at the margins of global value chains and experienced poor economic and social outcomes and ecological degradation. This development pattern can be explained by a lack of GVC integration, which generates *(i)* less income (directly through low GVC value capture, indirectly through less productive investment) to redistribute, *(ii)* a lack of access to more ecologically-efficient technologies, which results in more pollution-intensive production processes and/or specialization in more pollution-intensive activities, leading to high local ecological degradation and *(iii)* an external ecological balance that is highly heterogenous.

Cluster 2, which we label ***ecologically perverse upgrading***, exhibits an average integration into GVCs with positive productive and GVC value capture. Socio-economic outcomes, in turn, present average values (cf. Fig. 2), although this is mainly due to the fact that these countries started the period of analysis with low socioeconomic standards. The evolution of the majority of the socioeconomic variables (cf. Table 5) shows a clear pattern of social upgrading. However, these favourable developments are obtained at the cost of higher-than-average local ecological degradation, which is at least in part the result of a negative external ecological balance. The logic of this development pattern is economic and socio-economic upgrading through integration in GVCs. While it may improve incomes for the general population in the medium term, it also implies ongoing local ecological degradation.

Cluster 3, which we label ***reproduction of the core***, is composed of countries that are benefitting the most from integration into GVCs in terms of value capture, socioeconomic outcomes and productive development relative to others, while suffering less from ecological degradation. This is the story of most developed countries and some of their immediate periphery in eastern Europe. The rationale of this development pattern is that they increased their participation in GVCs while positioning themselves withing high-value, lower ecological impact sectors. Value capture based largely on high-tech production, services (finance, marketing, and branding) as well as monopoly control over patents, meant that domestic ecological impacts were kept to a minimum. This sustained an already relatively high standard of living and provided outsized incomes that enabled greater access to consume ('dirty') foreign products.

However, contrary to cluster 2, these socio-economic benefits rely to a greater extent on an already-existing productive capacity. Moreover, they escape the immediate ecological costs of their consumption by imposing the ecological burden on other peripheral countries.

4.2. Possible relational dynamics

Although our empirical study does not demonstrate causal effects, it reveals patterns suggesting a relational dynamic between the three classes that are broadly aligned with our initial hypotheses.

First, contrary what we expected from Hypothesis 1, productive development is associated with GVC participation not only for low-income economies but also for high-income countries, as shown in

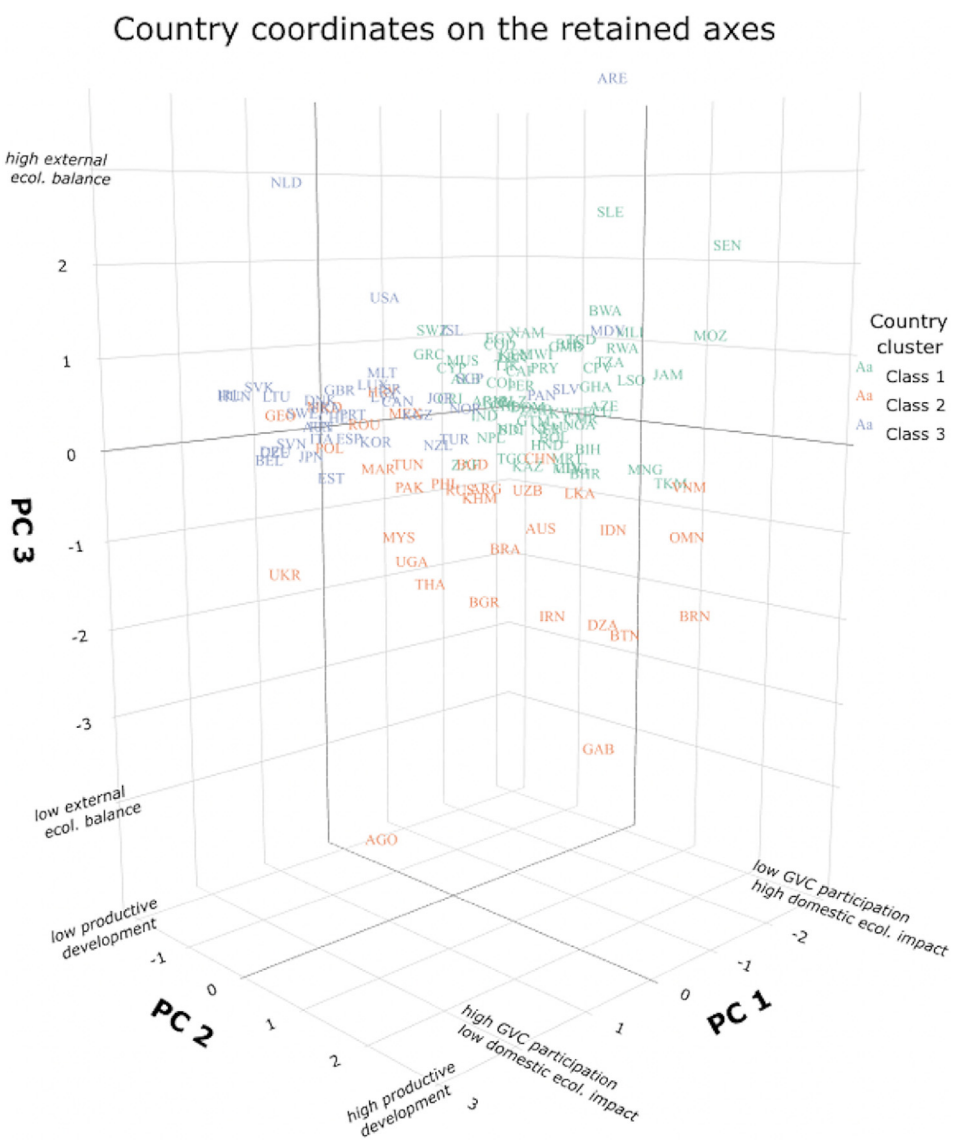

Fig. 3. 3D representation of our clusters. Only the variable or two contributing most of the information to the axes are listed on the respective axis labels. For PC1, this is GVC participation (30%) and domestic ecological impacts (22%). For PC2, this is productive development (64%); and for PC3, it is the external ecological balance (83%).

Table 4
Median starting 1995 values for all underlying variables by cluster and for the sample as a whole.

	Initial 1995 level			
	Overall	Cluster 1	Cluster 2	Cluster 3
GVC participation	0.18	0.13	0.17	0.32
GVC value capture	0.34	0.22	0.44	0.51
Investment rate	21.98	21.29	22.44	23.33
Capital stock	21467.8	12220.3	21707.4	134637.3
Employment rate	93.01	93.82	92.90	92.84
Median income	1988.7	1353.99	1940.7	9335.4
Labour share	0.56	0.55	0.56	0.65
Inverse Palma ratio	−5.07	−6.70	−5.04	−2.49
Domestic material extraction per km2	369.55	223.45	438.77	1052.8
Domestic local pollution intensity of GDP	0.0194	0.0313	0.0193	0.0112
Domestic biodiversity loss per km2	2.45e-08	4.64e-08	2.13e-08	1.02e-08
Domestic CO2 intensity of GDP	0.2221	0.1699	0.2437	0.2768
Materials external balance	−0.0494	−0.2370	−0.2278	0.4127
Pollution external balance	0.1798	0.2660	−0.0073	0.1867
Biodiversity external balance	−0.0461	−0.1085	−0.0759	0.6658
CO2 external balance	0.1781	0.2423	−0.0068	0.1942

Table 5
Median 1995–2015 variation rates for all underlying variables by cluster and for the whole sample.

	1995–2015 variation rate (%)			
	Overall	Cluster 1	Cluster 2	Cluster 3
GVC participation	10.76	−4.14	27.95	58.73
GVC value capture	9.51	17.26	10.61	4.74
Investment rate	6.90	16.92	11.63	−4.73
Capital stock	122.99	129.65	164.54	72.93
Employment rate	0.31	0.19	0.10	0.82
Median income	58.47	67.11	64.67	48.51
Labor share	0.12	0.12	0.48	−0.13
Inverse Palma ratio	0.79	11.71	4.25	−13.0
Domestic materials extraction per km^2	74.10	95.10	75.57	21.24
Domestic local pollution intensity of GDP	−52.04	−41.82	−52.04	−66.83
Domestic biodiversity loss per km^2	1.94	3.64	2.65	−2.23
Domestic CO2 intensity of GDP	−21.92	−6.93	−10.22	−36.0
Materials external balance	11.91	−21.88	2.52	34.52
Pollution external balance	−0.64	−6.88	−8.65	24.94
Biodiversity external balance	2.10	−5.62	5.68	2.99
CO2 external balance	−5.88	−12.40	−5.88	19.40

Table 6
Median final 2015 values for all underlying variables by cluster and for the sample as a whole.

	Final 2015 level			
	Overall	Cluster 1	Cluster 2	Cluster 3
GVC participation	0.20	0.13	0.22	0.48
GVC value capture	0.41	0.23	0.48	0.55
Investment rate	23.77	23.68	25.13	23.10
Capital stock	61167.3	24637.8	66375.45	231001.3
Employment rate	93.85	94.15	93.95	93.72
Median income	3886.8	2118.32	3692.33	13711.61
Labour share	0.57	0.55	0.56	0.65
Inverse Palma ratio	−4.57	−6.6	−4.29	−2.95
Domestic material extraction per km2	728.92	441.43	691.98	1368.34
Domestic local pollution intensity of GDP	0.0088	0.0207	0.0104	0.0035
Domestic biodiversity loss per km2	2.6e-08	4.73e-08	2.04e-08	9.89e-09
Domestic CO2 intensity of GDP	0.1707	0.1504	0.2282	0.1603
Materials external balance	−0.0468	−0.2223	−0.1791	0.5306
Pollution external balance	0.1721	0.2342	−0.0048	0.2253
Biodiversity external balance	0.0203	−0.1073	−0.1030	0.7874
CO2 external balance	0.1626	0.2295	−0.0045	0.2138

Table 7
Absolute amount of domestic production-based environmental impact by cluster and for the sample as a whole.

		Material extraction (billion tons)	CO2 Emissions (trillion kg)	Local pollutants (kg)	Biodiversity loss (potentially disappeared fraction of species)	GDP (trillion constant 2017 $USD PPP)
Initial 1995 levels	Sample	46.13	20.71	925,377	3.36	54.63
	Cluster 1	8.43	2.07	188,290	1.41	6.27
	Cluster 2	22.52	7.73	421,352	1.62	14.98
	Cluster 3	15.17	10.91	315,735	0.33	33.38
Percentage change, 1995–2015	Sample	81.29	52.85	6.83	4.04	99.38
	Cluster 1	77.36	119.34	52.53	2.06	163.85
	Cluster 2	135.23	109.12	24.52	7.46	174.67
	Cluster 3	3.40	0.34	−44.04	−4.35	53.47
Final 2015 levels	Sample	83.63	31.66	988,555	3.50	108.92
	Cluster 1	14.95	4.54	287,190	1.44	16.55
	Cluster 2	52.99	16.17	524,675	1.75	41.15
	Cluster 3	15.69	10.94	176,689	0.31	51.22

Table 8
The compossibility of three observed development patterns.

	Curse of GVC marginalization	Ecologically perverse upgrading	Reproduction of the core
GVC participation	Low	Not distinctive	High
GVC value capture	Low	High	High
Productive development	Low	Above average	High
Socio-economic development	Low	Not distinctive	High
Domestic ecological degradation	High	Not distinctive	Low
External balance of ecological degradation	Not distinctive	Negative	Positive

Fig. 2. This indicates that GVCs are a vector of productive development.

Second, we consider the contradictory channels through which GVC participation impacts socio-economic outcomes (Hypothesis 2). Our analysis suggests that these are broadly aligned with productive dynamics: for marginalized countries, a lack of integration within GVCs meant poor socio-economic outcomes, while those countries capable of integration saw mostly positive gains. However, in core countries, the positive positioning reflects mostly an initially favorable situation rather than an improving dynamic.

Third, we posited a negative global ecological impact of GVC participation with some relative gains to the core at the expense of the periphery. Hypothesis 3 is therefore partially corroborated but requires further elaboration and some qualification. This is where our study brings some new insights to the ecologically unequal exchange framework and to the understanding of the GVC-environment nexus.

4.3. Incorporating the GVC analysis into EUE

According to EUE, ecological imbalances result from exchanges in core-periphery trade and the development of modern technologies. The core specializes in technologically-advanced, high-value-added production. This gives it greater purchasing power over peripheral resources. While our results confirm a clear asymmetry in ecological degradation between high-income and low-income economies, we also find reasons to nuance the traditional EUE narrative: we distinguish between two types of peripheries.

First, we locate the distribution of environmental benefits and burdens within chains of value production. Countries are differently able to integrate and capture value along production chains. This offers vastly different capacities to either accept or displace environmental impacts. We therefore provide evidence that the distribution of environmental impacts is intimately related to the global division of labor. These two dynamics appear to be interdependent and co-evolving at the world scale, a stylized fact increasingly recognized in the literature on GVCs (Althouse and Svartzman, 2022; Baglioni and Campling, 2017). Global environmental inequalities then arise through the uneven geography of value capture. Ecologically unequal outcomes are thereby shaped by socio-technical relations, institutional regulations, and historical power struggles.

Second, we show that peripheral countries that increase their participation in GVCs tend to do so at a high environmental cost. While this finding is broadly aligned with the EUE literature, we clearly highlight the patterns through which the geographical distribution of global production processes reinforces environmental inequalities. We show that integrating within GVCs can upgrade productive structures and socio-economic outcomes but does not improve environmental quality for these countries.

Third, we highlight a group of countries that appear to be 'marginalized' from GVC dynamics. These countries are participating less in trade in general compared to other countries and/or are specializing in non-GVC related primary products. This group of low-income economies also suffers from high levels of ecological degradation. Low domestic environmental safeguards due to a weak environmental regulatory state, use of highly inefficient technology and/or resulting specialization in pollution-intensive activities could explain this outcome at any level of trade.

What is puzzling from the point of view of EUE is that this cluster experiences a neutral external ecological balance, on average. Further analysis in future research is required to fully account for this fact. One can nonetheless mention two potential explanations. First, the EUE and environmental load displacement literature shows that foreign direct investment allows high income countries to relocate their ecological impacts abroad (Givens and Huang, 2021). However, specialization in environmentally-intensive low-value-added exports may be 'balanced' materially by importing greater amounts of higher-value goods if the countries exhibit large current account deficits, funded by external finance and growing indebtedness. This would imply that foreign finance could be, at least in the short-term, a means of displacing environmental impacts by the marginalized countries. Second, there may be instances where value-added processes that are further along the chain are more polluting than previous stages. More precisely, these countries may rely on imports for energy and other resource-intensive basic materials while their exports of primary products do not incorporate industrial processes that are intensive in resources, but instead rely extensively on labour.

Our study also attempts to tease out the differences between environmental impacts, GVC participation, and efficiency that cannot be seen from within the EUE framework. Looking back at Table 1, we designated the domestic and global ecological differences for the core and periphery based on changes in reshoring, offshoring, and efficiency. All things equal, the cases of what show up as increased EUE from an accounting perspective would not *necessarily* lead to an increasing global footprint.

Table 7 shows that, at the global level, the correlation between economic growth and environmental impacts is largely positive for CO2 and materials extraction and moderately positive for biodiversity and other pollutants. At the global level, there are no signs of absolute decoupling for any of the variables relative to GDP. While core countries do exhibit some signs of absolute decoupling (particularly for biodiversity and pollutants) domestically, this must be considered along with the other groups' domestic increases and the net external ecological balances of each cluster. Decoupling in the core has largely come about by offshoring environmental impacts to the periphery.

Interestingly, neither the *curse of marginalization* nor the *ecologically perverse upgrading* groups saw reduced environmental impacts in absolute terms for any of the environmental variables. These findings imply that even if efficiency increases were forthcoming in the non-core countries, they were overwhelmed by increases in environmentally-intensive production.

It is also worth noting that the *ecologically perverse upgrading* group has a sharp increase across all four production-based environmental variables. This suggests that a large share of the core's domestic decreases in environmental impacts is achieved through EUE, rather than via efficiency gains. Nevertheless, even this group of peripheral countries moderately involved in GVCs has managed to relatively decouple for two of the four variables (local pollutants and biodiversity losses). It is therefore possible that some efficiency gains and/or legal restrictions (e.g., environmental regulations to limit certain types of pollution, the development of protected conservation areas) could have offset some of the environmental pressures.

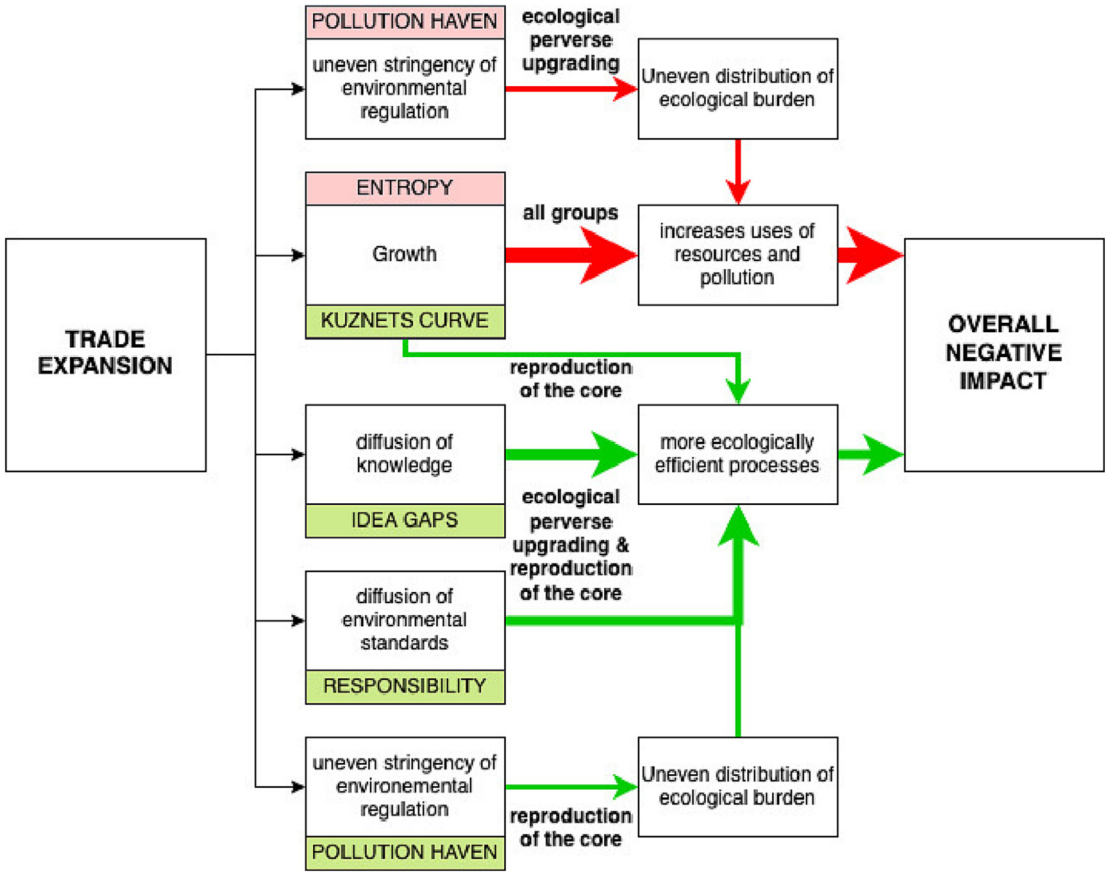

Fig. 4. Channels driving the overall global negative ecological impact of trade expansion (Authors' elaboration).

Overall, the study suggests that while some increases in efficiency may be playing a role in bringing about environmental improvements, the periphery's increasing integration within GVCs is a major factor in driving increased local and global environmental burdens. While this conclusion resonates with those in the EUE framework, we nonetheless further and refine the EUE literature by identifying the role of GVCs in driving environmental asymmetries.

4.4. The trade-environment nexus revisited

Our analysis offers fresh insights concerning the general consequences of participating in global trade from the ecological point of view (Fig. 1 in Appendix 1). Depending on the clusters considered, the dynamics are not the same, which allows for a new representation of the channels linking trade and ecological outcomes (Fig. 4).

Countries with limited GVC participation, belonging to the group we label *curse of GVC marginalization*, do not suffer from a large "uneven distribution of ecological burden" effect. Nor do they benefit from the positive ecological impacts of GVC participation in terms of more ecologically-efficient processes and higher environmental standards. As a result, the main driver through which trade impacts the environment is through the growth channel: entropy dynamics are then the primary driver of domestic ecological degradation.

Countries pertaining to the *ecologically perverse upgrading* group suffer from a negative ecological external balance and moderate levels of domestic ecological degradation in a context of greater involvement in GVCs than the former group. This outcome is very informative, since it shows that the negative ecological impacts of trade occur through the entropy channel and the pollution haven mechanism. These dynamics seem to prevail for cluster 2's peripheral countries, undermining the potential benefits of improved environmental standards and more environmentally-efficient technologies.

Finally, countries pertaining to the *reproduction of the core* group exhibit much better ecological outcomes than other groups, both in terms of domestic impact and the ecological external balance. For these countries, concentration in low-impact services and end-of-chain production alongside the diffusion of more ecologically-efficient processes and higher environmental standards can play a role to domestically counter-balance the negative entropy effect of growth. However, enhanced efficiencies rely mostly on the pollution haven channel.

The green side of the pollution haven channel did not appear in Fig. 1 (in Appendix 1), since it was not explicitly mentioned by the OECD. It needs nonetheless to be considered to stress that there is a zero-sum game dimension in the ecological impact of trade.

Overall, considering that the entropy channel plays a role for all groups while the net positive impact is limited to the *reproduction of the core* group, this framework suggest that the overall ecological impact of trade is negative.

5. Conclusion

This article has provided a theoretical and empirical investigation into the uneven environmental transformations associated with different modes of insertion within global trade. We analyzed compossible development patterns within GVCs for 133 countries between 1995 and 2015, using data covering six key dimensions: GVC participation, GVC value capture, productive development, socio-economic development, domestic environmental impact, and international environmental balance. Our results confirm that GVCs are a major driver of unequal socio-ecological developments.

While integration within GVCs may enhance socio-economic indicators for some countries, there is a general trend towards increasing polarization and ecologically unequal exchange. In other words, while in socio-economic terms GVC participation is a positive-sum but asymmetrical game (some countries benefit more than others), in ecological terms we do find some zero-sum game dynamics.

The cluster analysis allows us to identify three distinct development patterns associated with integration within GVCs*: the curse of GVC marginalization, ecologically perverse upgrading,* and a *reproduction of the core*. Countries succumbing to the *curse of GVC marginalization* demonstrated decreases or minor increases in GVC participation and value capture, low productive development, poor socioeconomic outcomes, and high domestic ecological degradation. This class of countries was thereby isolated from the potential socio-economic benefits of GVC integration, yet also exhibited relatively high levels of domestic ecological burden.

Those countries whose development is best described through *ecologically perverse upgrading* were most capable of increasing their productive capacity and capturing socio-economic benefits associated with their GVC participation. However, this development pattern is linked to an increase in domestic ecological degradation and a decline in its external environmental balance. This implies that improvements in social and economic outcomes were driven in large part by exploiting domestic natural resources for export to the rest of the world.

The *reproduction of the core* dynamic refers primarily to high-income countries whose dominant position in GVCs is demonstrated by increases in levels of GVC participation and value capture. Moreover, this group is characterized by strong levels of socio-economic and productive development, relatively low domestic degradation, and a high external ecological balance. The core's position within production networks appears to allow it to sustain high levels of profitability while offshoring ecological impacts abroad.

Overall, our results imply a difficult road ahead for achieving more ecologically balanced patterns of socio-economic development. On the one hand, high levels of participation in global production networks may bring social benefits. Yet they are associated with a concomitant increase in environmental exploitation, whether domestic (the periphery) or abroad (the core). On the other hand, those countries not integrating into GVCs remain vulnerable to domestic ecological degradation and low levels of socio-economic development.

We therefore conclude that while integration within GVCs may provide some opportunities to relieve *domestic* environmental burdens for peripheral countries (e.g., through efficiency improvements), these are ultimately ineffective at relieving ecological pressures globally. The proliferation of GVCs appear to be an important institutional mechanism through which peripheries are environmentally subordinated to the benefit of the core.

Data availability

The data is available on GitHub (see below).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

Appendix 1 and 2 containing supplementary data to this article can be found online at https://doi.org/10.1016/j.worlddev.2023.106308.

A repository containing the R code and material for this article is available on GitHub: https://github.com/LouisonCF/Ecologically_unequal_exchange_development_GVCs/tree/main.

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