Rethinking trade for the ecological transition: Quantifying the trade drivers of planetary boundaries

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ABSTRACT (150 words)

The latest Planetary Boundaries update portrays an alarming global ecological situation in which six of the nine boundaries are transgressed. As a large share of human economic activities is enabled by international trade, this paper aims to analyze the footprints of global trade over the planetary boundaries. Using a multi-regional input-output database, we calculate environmental footprints embodied in trade relations related to the different planetary boundaries for different countries and economic activities (economic sectors) through a modified method of consumption-based accounting. Results indicate that the different global economic regions have heterogenous footprints, occupying different positions along a multidimensional spectrum of pressures over the different planetary boundaries. These geographical differences largely reflect the different sectoral economic structure of the countries, as the pressure over planetary boundaries are sector specific.

INTRODUCTION (3500 words up to Methods)

This paper aims at understanding global trade's pressure over the planetary boundaries, which accounts for the nine processes that are critical for maintaining the stability and resilience of Earth system as a whole. The latest Planetary Boundaries update portrays an alarming global ecological situation in which six of the nine boundaries are transgressed[1]. By identifying the processes that are critical for maintaining the stability and resilience of the Earth system as a whole, the planetary boundaries framework equates a multi-level range of ecological dynamics[1,2,3]. However the Earth System dynamics is itself mainly driven by socio-economic dynamics at global scale, which are themselves structured around trade patterns between geographies and products.

Global economic relations are indeed the result of historical patterns of ecological, productive and financial exchanges[4,5]. Depending on the observed planetary boundary, countries can appear as resource supplier, feeding global productive chains or consumer of the resource, exerting demand that keeps the global economy operating. One country could be, for example, an exporter of "water" and an importer of "land" at the same time. Therefore, different countries and economic sectors contribute directly and indirectly by pressuring/easing planetary boundaries through their commercial relations with other economies.

International trade dynamics[6] are an essential determinant of global production and consumption patterns. It creates a strong hysteresis effect for both exporting and importing countries. The exports of resources generate income, jobs, fiscal revenues and foreign exchange that can be an essential macroeconomic stabilizer of a country[7], while imports of the same commodities and their transformation or consumption can become an essential way of sustaining certain levels of well-being[8].

Social well-being and planetary boundaries dynamics should be analysed together. The pioneer attempt to subscribe human economic needs and activities to the boundaries of the Earth System is found in Raworth's proposition of the "safe and just space for humanity"[9], in which the ceiling of environmental degradation provided by the planetary boundaries is complemented with a floor of social well-being to be achieved. Since then, multiple studies connecting the planetary boundaries framework with the economy have been centred around downscaling planetary boundaries to lower political decision-making levels, such as national, regional, sectoral and even municipal[10,11]. Although the best downscaling methodology to be employed is still the subject of ongoing debate[12,13,14,15,16], results of analysis carried out for different scales and scenarios display a worrying trend of multiple boundaries being crossed[10,16,17,18,19,20,21,22,23,24,25] and no strongly sustainable social well-being dynamics.

Another strand of research has focused on the study of provisioning systems[26,27] and the question of how to move towards new economic institutions and forms of organisation that would allow humanity to achieve a social floor of well-being without overshooting the planetary boundaries. Achieving a "good life for all within planetary boundaries" requires policies capable of shifting humanity towards new economic models[28] as currently no country is able to meet basic needs for its citizens without overshooting multiple planetary boundaries[29,30].

In this paper we aim at analysing the planetary boundaries footprint of global trade and understand the geographical and sectoral drivers of this footprint. Although some previously published research assesses the impact of global trade on individual boundaries[18,20,31,32], they fall short of addressing the multidimensional spectrum of different countries and economic sectors impacting the different planetary boundaries in different directions. Drawing on the ecological variables employed in the original planetary boundaries' studies, we select key variables to separately estimate the pressure exerted on each one of the six already exceeded planetary boundaries.

We assume that the pressure over the boundaries generated by global trade is driven by the demand from importing countries but attributed to the exporting countries. We use a modified form of the traditional consumption-based footprint accounting[19,20,32,33,34,35], in which the sum of direct and indirect (embodied in domestic and imported inputs) pressure that countries' final demand exerts on the multidimensional spectrum of planetary boundaries is calculated. Conversely to the traditional form, our modified method is thus able to consider both trade of intermediary goods and of final consumption, accounting for all economic goods that are internationally traded at least once during their production cycle. We also disentangle the key economic sectors and activities that are leading the pressure for each planetary boundary. The ecological transition consists of a process of economic structural change[7, 36] in which economic sectors pressuring boundaries are expected to decline, or undergo fundamental transformations in their productive techniques. Therefore, identifying the major economic activities and sectors driving the pressure over each boundary is valuable as these sectors are the ones to be targeted by transition policies for the success of the ecological transition.

Objectives and variable selection

The original planetary boundaries works[1,2,3] define limits, or tipping points beyond which the Earth system dynamics radically shifts to conditions that become incompatible with human life. When trying to link economic activities (flow variables) to planetary boundaries (stock variables), scenario studies[17,21] usually take the stock threshold value established by the planetary boundaries framework and distribute it across the period encompassed by the economic analysis. However, as we do not aim to assess whether the pressure exerted by global trade flows are above yearly defined boundary levels, we directly use flow variables for the year 2021 in order to analyse which countries and sectors' activities pressured the most the planetary boundaries during the selected period.

We select the following proxy variable to measure the different planetary boundaries footprints. Change in biosphere integrity is measured in terms of potentially disappeared fraction (PDF) of biodiversity loss. Land use is measured in terms of hectares used in production. Climate change is measured in GHG emissions in kilotonnes. The global freshwater boundary is measured both with water stress and blue water consumption calculated in million m3 H2O equivalents. Nitrogen and phosphorus loading calculations are made by estimating the amount of embodied nitrogen and phosphorus measured in tonnes in agriculture sectors' output. Following suggestions in the literature[36], the novel entities boundary is estimated through the amount of embodied non-energy materials employed in the chemicals sector. This approach aligns with extensive research on environmental footprint indicators which indicates that resource footprints are good proxies for measuring environmental damage[38,39]. A summary of the variables employed is found in Table 1 below.

Although the variables selected in this paper are not exactly the same as the ones employed by the planetary boundaries' original framework, they are all able to provide an approximated and reliable measurement of the pressure exerted by the economic activity over each one specific boundary during the selected period. Taking the boundary of "change in biosphere integrity" as an example, it is expected that elevated values of the potentially disappeared fraction (PDF) variable are correlated with loss of genetic diversity and functional integrity and, consequently, will lead to increasing pressure over the earth system process towards the boundary.

Earth system process	**Variables employed in planetary boundaries' latest assessment[1]**	**Variables employed in this study**
Biogeochemical flows: P and N cycles	• Phosphate global: P flow from freshwater systems into the ocean • Phosphate regional: P flow from fertilisers to erodible soils (Tg of P year−1) • Nitrogen global: industrial and intentional fixation of N (Tg of N year−1)	• Fertiliser minerals directly and indirectly embodied in agriculture production (tonnes)
Climate change	• Atmospheric CO2 concentration (ppm CO2) • Total anthropogenic radiative forcing at top-of-atmosphere (W m−2)	• Total GHG emissions provided by EDGAR (kilotonnes CO2 equivalent)

Change in biosphere integrity	• Genetic diversity: E/MSY • Functional integrity: measured as energy available to ecosystems (NPP) (% HANPP)	• Potentially Disappeared Fraction (PDF)
Freshwater change	• Blue water: human induced disturbance of blue water flow • Green water: human induced disturbance of water available to plants (% land area with deviations from preindustrial variability)	• Agriculture and non-agriculture blue water consumption (million m3 H2Oeq) • Agriculture and non-agriculture water stress (million m3 H2Oeq)
Land system change	• Global: area of forested land as the percentage of original forest cover • Biome: area of forested land as the percentage of potential forest (% area remaining)	• Total area used by the economic activity (1000 ha)
Novel entities	• Percentage of synthetic chemicals released to the environment without adequate safety testing	• Non-energy material footprint embodied in chemical production

Table 1: Variables employed in planetary boundaries' latest assessment vs. variables employed in this study.

RESULTS

Global trade pressure over planetary boundaries

For the year of 2021, global trade was responsible for 20.2% of the boundary pressure on biogeochemical flows, 25.9% on biosphere integrity, 28.6% on land system change, 26.6% on climate change and 50.6% on novel entities. For the freshwater change boundary, global trade was responsible for 22.0% of the pressure on blue water consumption and 19.5% on water stress. In Figure 1 the share of the global trade pressure over the planetary boundaries is decomposed into three categories: goods internationally traded during production, goods traded for final consumption, and goods traded both during production and for final consumption.

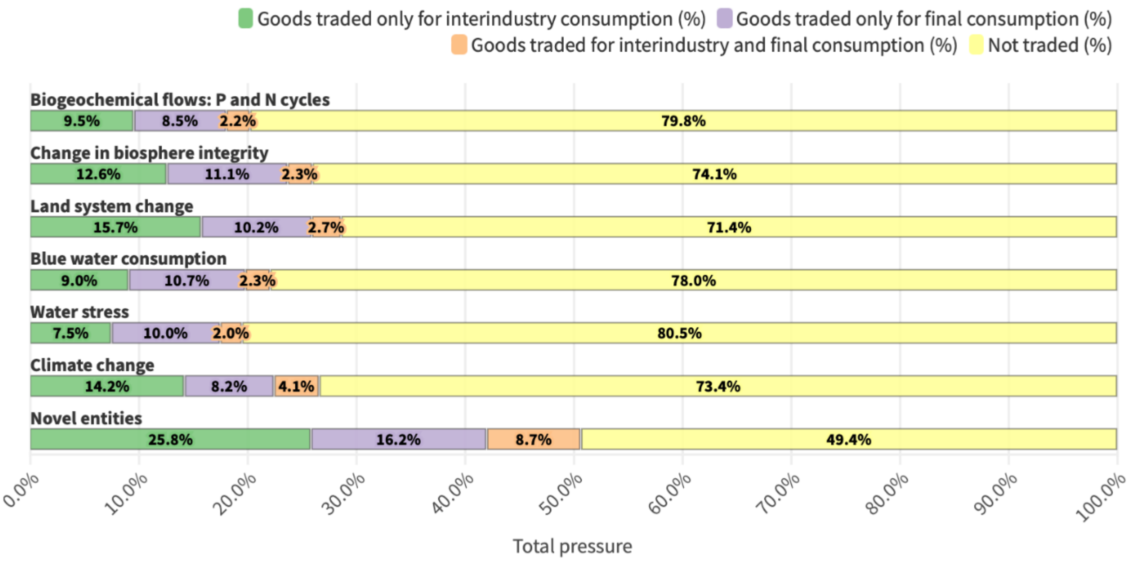

Figure 1: Share of pressure exerted by intercountry traded goods. Source: GLORIA environmental extended multi-regional input-output database. **Note:** *Not traded goods* are goods whose productive chain and final consumption

take place inside only one country. *Goods traded for interindustry and final consumption* are goods whose productive chain involves cross-border trade and final consumption takes the form of an import. *Goods traded only for final consumption* are goods whose productive chain takes place in only one country and final demand takes the form of an import. *Goods traded only for interindustry consumption* are goods whose productive chain involves cross-border trade and final demand consists of a domestic purchase.

The pressure on the boundaries is mainly driven by import consumption demand in high- and middle-income countries (Figure 2). The group of high-income countries, for instance, is responsible for around 42% of the pressure over the change in biosphere integrity boundary and for 61% over the novel entities boundary. High- and middle-income countries are driving together at least 78% of the trade pressure over all the analysed boundaries.

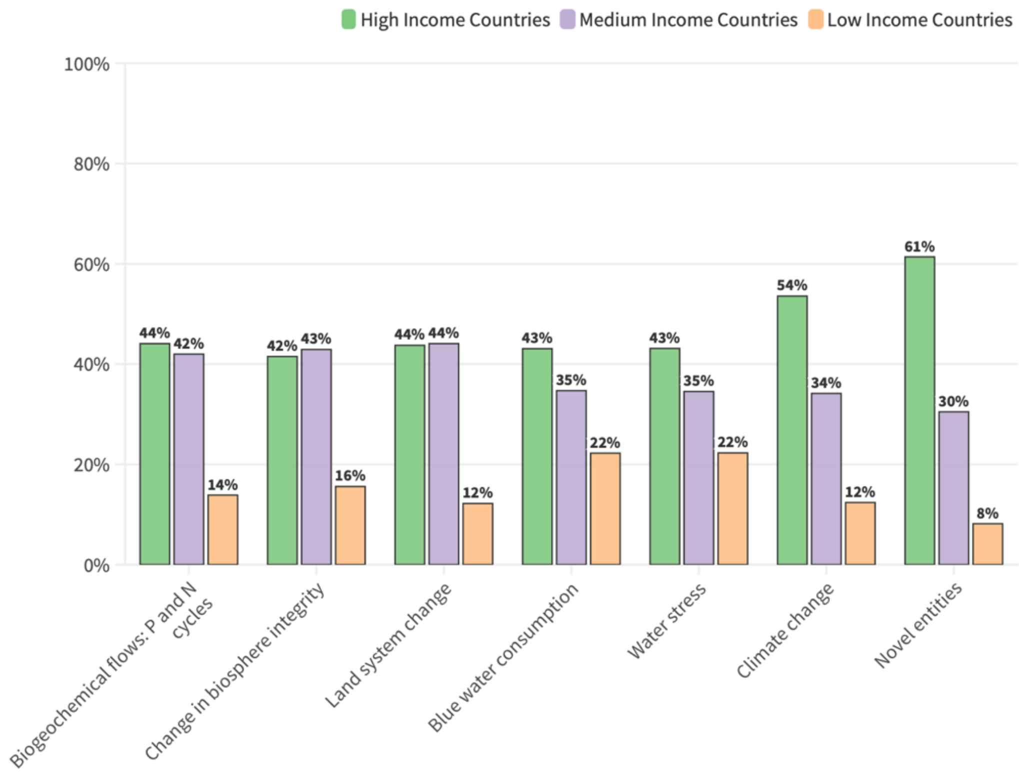

Figure 2: Trade pressure on the planetary boundaries exerted by different income groups of countries. Source: GLORIA environmental extended multi-regional input-output database

Biogeochemical flows: P and N cycles

More than 44% of the global trade pressure over the biogeochemical flows' boundary is driven by the import consumption pressure of high-income countries. 52.5% of all the pressure takes place in middle- and low-income East Asian, Pacific, Latin American and Caribbean countries in the form of embodied fertiliser usage in production. While high-income countries from East Asia and Pacific, and Europe and Central Asia, have an import to export ratios of embodied fertilisers in agriculture production of 8.2 and 2.9 respectively, middle- and low-income Latin American countries, on the contrary, export around 4.1 times more than import, which reveals large inequalities and geographical dependencies among different groups of countries. At the country level, China and the US are responsible for 24.4% and 11.7% of the embodied fertiliser import pressure, respectively, followed by Japan with 5.2% and Germany with 3.5%. On the export side, Brazil exports 17.3% of the total trade pressure, followed by China with 15.6%, the US with 15.1%, Peru with 7.6% and Canada with 7.2%. Sankey plots summarizing the results for all the boundaries are displayed in Figure 3.

Change in biosphere integrity

The results for the biosphere integrity boundary follow similar patterns as the biogeochemical flows one as pressure over the biosphere integrity mostly flows from middle- and low-income East Asian, Pacific, Latin American and Caribbean countries countries towards high-income regions and middle and middle- and low-income East Asian and Pacific countries themselves. Together, Latin American and East Asian and Pacific middle- and low-income countries provide 52.4% of all the products that satisfy the import demand pressure over the boundary. Middle-income and low-income Latin American countries display an import to export ratio of only 0.23, meaning that the region exports 4.3 times more pressure than it imports. The global potential loss of species caused by global trade is geographically concentrated in Australia (15.2%), Brazil (11.9%) and Indonesia (5.9%), and driven mostly by import consumption pressure from China (25.2%), the US (11.2%) and Japan (5.4%).

Land system change

High-income countries together with middle- and low-income East Asian and Pacific countries account for 78.7% of all import demand pressure over the land system change boundary. Although spread throughout the different groups of countries in a more evenly way in comparison to other boundary pressures, the land system change pressure takes place mostly in spatially large countries. The group of Australia (16%), Canada (13.5%), the US (10.3%), Russia (10%) and Brazil (5.5%) concentrates more than half of global land use and change driven by global trade. This land use is embodied in products that are mostly consumed in China (28.9%), the US (13.4%), Japan (5.2%) and Korea (2.7%).

Freshwater change

51.3% of blue water consumption and 57.7% of water stress driven by global trade take place in middle- and low-income East and South Asian, Pacific, Middle Eastern and North African countries. High-income countries together are responsible for 42.7% of total import consumption pressure over blue water consumption, and for 42.8% over water stress. In terms of individual countries, China, the US and Iran are the ones that exert most pressure over the freshwater change boundary, both in terms of blue water consumption and water stress. On the exporting side, India is isolated as the largest exporter of products that embody blue water (21.3%) and water stress (21%), followed by China and the US.

Climate change

The import consumption pressure over the climate change boundary is led by high-income European and Central Asian countries (21.9%), followed by Middle and low-income East Asian and Pacific countries (20.5%), North American countries (15.9%) and high-income East Asian and Pacific countries (11.5%). Country groups of Sub-Saharian Africa and of middle- and low-income Latin American and the Caribbean, and Middle East and North Africa account for only 13.7% of the global import pressure over this boundary. This inequality is expressed in the import to export ratios of the different regions, as high-income European and Central Asian, and East Asian and Pacific countries have import to export ratios of 2.0, while the same values for the groups of Sub-Saharian Africa and of middle- and low-income Latin American and the Caribbean, and Middle East and North Africa are 0.6, 0.7 and 0.7, respectively. China (18.9%), the US (13.6%) and Russia (6.9%) are the largest exporters of GHG emissions. These emissions are driven by import consumption pressure stemming mainly from China (14%), the US (13.6%), Japan (4.9%), India (4.7%) and Germany (4%).

Novel entities

Pressure results for the novel entities boundary are relatively different when compared to other boundaries. 28% of the import consumption driving the pressure over the boundary is generated in high-income European and Central Asian countries, 21% in North American countries, and 17.8% in middle- and low-income East Asian and Pacific countries. More than 40% of this pressure (41.4%) takes place in high-income European and Central Asian countries. Import to export ratios are somewhat reversed for this boundary, as Sub-Saharian, middle- and low-income Latin American and Caribbean

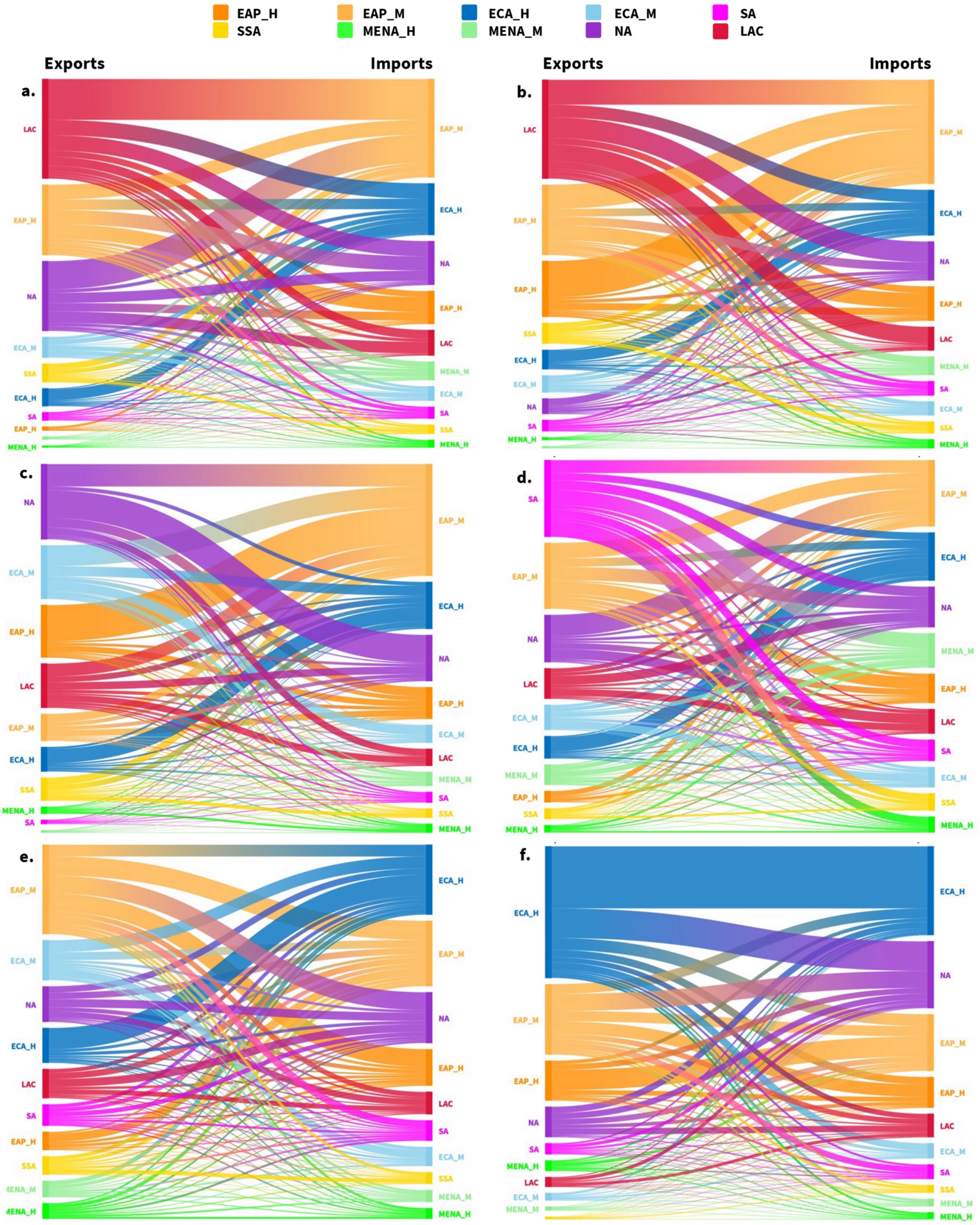

Figure 3: Sankey diagram of global trade's pressure over the planetary boundaries. a. Biogeochemical flows, b. Biosphere integrity, c. Land use change, d. Freshwater change in terms of blue water consumption, e. Climate change, f. Novel entities. **Note:** EAP_H: High-income East Asia and Pacific, EAP_M: Middle- and low-income East Asia and Pacific, ECA_H: High-income Europe and Central Asia, ECA_M: Middle- and low-income Europe and Central Asia, SA: South Asia, SSA: Sub-Saharian Africa, MENA_H: High-income Middle East and North Africa, MENA_M: Middle- and low-income Middle East and North Africa, NA: North America, LAC: Latin America and the Caribbean. **Source:** GLORIA environmental extended multi-regional input-output database.

also has a high import to export ratio of 2.2. This value is led mainly by the US position as the largest importing country of material footprint embodied in chemical products, accounting for 18.4% of global trade's pressure over the novel entities boundary, and followed by China (12.8%), Germany (5.8%), Japan (4.4%) and France (3.4%). On the exporting side, China leads with 18.2%, followed by the US (8.3%), Germany (6.8%), Ireland (6.3%) and Switzerland (5.7%).

Similarities among boundary pressures and sectoral results

The results above reveal some similarities among the different boundaries in terms of the sources of pressure. We run a correlation analysis (See Annex A) that shows for instance, that the changes in biosphere integrity and land system present quite similar results in terms of the geoeconomic sources of the import pressure. The boundaries of biogeochemical flows and freshwater change also display moderate correlation with the boundaries of change in biosphere integrity and land system change. Conversely, the results for the boundaries of climate change and novel entities unveil little correlation with the other boundaries and a moderate correlation between both.

The main reason for these similarities lies in the sectoral compositions of the countries. Countries and regions with analogous sectoral import and export structures generate similar pressures over the planetary boundaries. Despite geographical differences in productivity that may lead to the same sector being responsible for a distinct level of pressure per unit of output when located in a different country, the analysis shows that the pressure exerted by global trade over the different boundaries is sector specific and, hence, associated with the trade of specific economic activities.

The cluster analysis run in Annex A indicates some relevant outlier sectors according to their level of pressure over the different planetary boundaries. The agricultural sector of "growing leguminous crops and oil seeds" is for example the major supplier to the global import consumption pressure on the boundaries of biogeochemical flows and change in biosphere integrity. The same sector is also exporting relevant shares of the pressure over land system change and of the blue water consumed by global trade. A group of economic activities related to forestry, logging, sawmill products and raising of animals is also related to the global import consumption pressure on land system change and biosphere integrity. With regard to the freshwater change boundary, the economic activities of cereal products and spices, aromatic and drug crops exports are driving the pressure over blue water consumption and water stress. Another group consisting of the sectors of growing fruits, nuts, maize, wheat and textile activities also plays a large role in pressuring multiple boundaries of biogeochemical flows, change in biosphere integrity and freshwater change. All in all, the results indicate that import consumption pressure over agricultural sectors plays a key role in pressuring multiple planetary boundaries.

The pressure on the novel entities and the climate change boundaries has different profiles. Economic sectors of basic organic chemicals, pharmaceuticals, medicinal products, dyes, paints, glues, detergents and other chemical products lead the pressure over the novel entities boundary. On a different note, the results for the climate change boundary reveal that multiple carbon intensive manufacturing sectors determine the import pressure on the boundary, ranging from hard coal, petroleum extraction and refining products to computers and electronic products, and machinery and equipment in general. The industry of ceramics is also largely related to the pressure on the boundary, together with other basic industries such as iron, steel and basic organic chemicals.

From the import consumption point of view, the sector of cereal products appears as an outlier pressuring the freshwater change and biosphere integrity boundaries, while the sectors of building construction and civil engineering construction are major drivers of pressure over land system change and climate change. On the novel entities boundary, pharmaceuticals and medicinal products alone drive almost a fifth of the pressure. Nevertheless, despite these outliers, there is more homogeneity among the sectors that drive the pressure over the different boundaries, something that can be observed in the correlation analysis (Annex A).

Earth system processes	**Major pressure exporting regions and countries**	**Major pressure importing regions and countries**	**Main economic sectors pressuring the boundary**
Biogeochemical flows: P and N cycles	• Middle- and low-income Latin American and the Caribbean • Middle- and low-income East Asia and Pacific • North America	• Middle- and low-income East Asia and Pacific • High-income Europe and Central Asia • North America	• Growing leguminous crops and oil seeds • Growing fruits, nuts, maize, cereals and wheat • Textiles and clothing • Alcoholic and other beverages
Change in biosphere integrity	• Middle- and low-income Latin American and the Caribbean • High-, Middle- and low- income East Asia and Pacific	• Middle- and low-income East Asia and Pacific • High-income Europe and Central Asia • North America	• Growing leguminous crops and oil seeds • Forestry, logging and sawmill products • Raising of animals and services to agriculture • Cereal and dairy products

Land system change	• Spatially large countries such as Australia, the US, Russia, China, Canada and Brazil	• Middle- and low-income East Asia and Pacific • High-income Europe and Central Asia • North America	• Forestry, logging and sawmill products • Raising of animals and services to agriculture • Growing leguminous crops and oil seeds • Building construction and civil engineering construction
Freshwater change	• South Asia led by India • Middle- and low-income East Asia and Pacific • North America	• Middle- and low-income East Asia and Pacific led by China • High-income Europe and Central Asia • North America • Middle East and North Africa led by Iran	• Cereal products • Growing leguminous crops and oil seeds • Growing spices, aromatic, drug and pharma ceutical crops • Growing fruits and nuts • Textiles and clothing
Climate change	• Middle- and low-income East Asia and Pacific led by China • North America led by the US • Middle- and low-Europe and Central Asia	• High-income countries led by the US • Middle- and low-income East Asia and Pacific led by China	• Electric power generation, transmission and distribution • Building construction and civil engineering construction • Ceramics and other ceramics • Basic iron, steel and organic chemicals • Petroleum extraction, refined products and hard coal • Raising of animals • Computers, electronic products, optical and precision instruments; machinery and equipment
Novel entities	• High-income group of countries led by EU countries • Middle- and low-income East Asia and Pacific led by China	• High-income Europe and Central Asia led by EU countries • North America countries led by the US	• Pharmaceuticals and medicinal products • Dyes, paints, glues, detergents and other chemical products • Basic organic chemicals and petrochemical products • Plastic products • Human health and social work activities • Building construction and civil engineering construction

Table 2: Summary of results

DISCUSSION

Our results provide a broad overview of the ecological footprint exerted by global trade over the planetary boundaries. They are in alignment with the results found in previous studies focused on specific boundaries, countries or sectors. Most notably, the pressure generated by global trade over the different planetary boundaries is unevenly distributed around the world in geographical terms. In alignment with past studies[31,40], we found a great divide among high-income and middle- and low-income countries as import demand for final consumption goods from the former leads to deterioration of Earth System processes taking place in the latter. Middle and low-income East Asia and Pacific countries, led by China, stand in between the groups, being a major importer and exporter of pressure for multiple analysed boundaries (Figure 4).

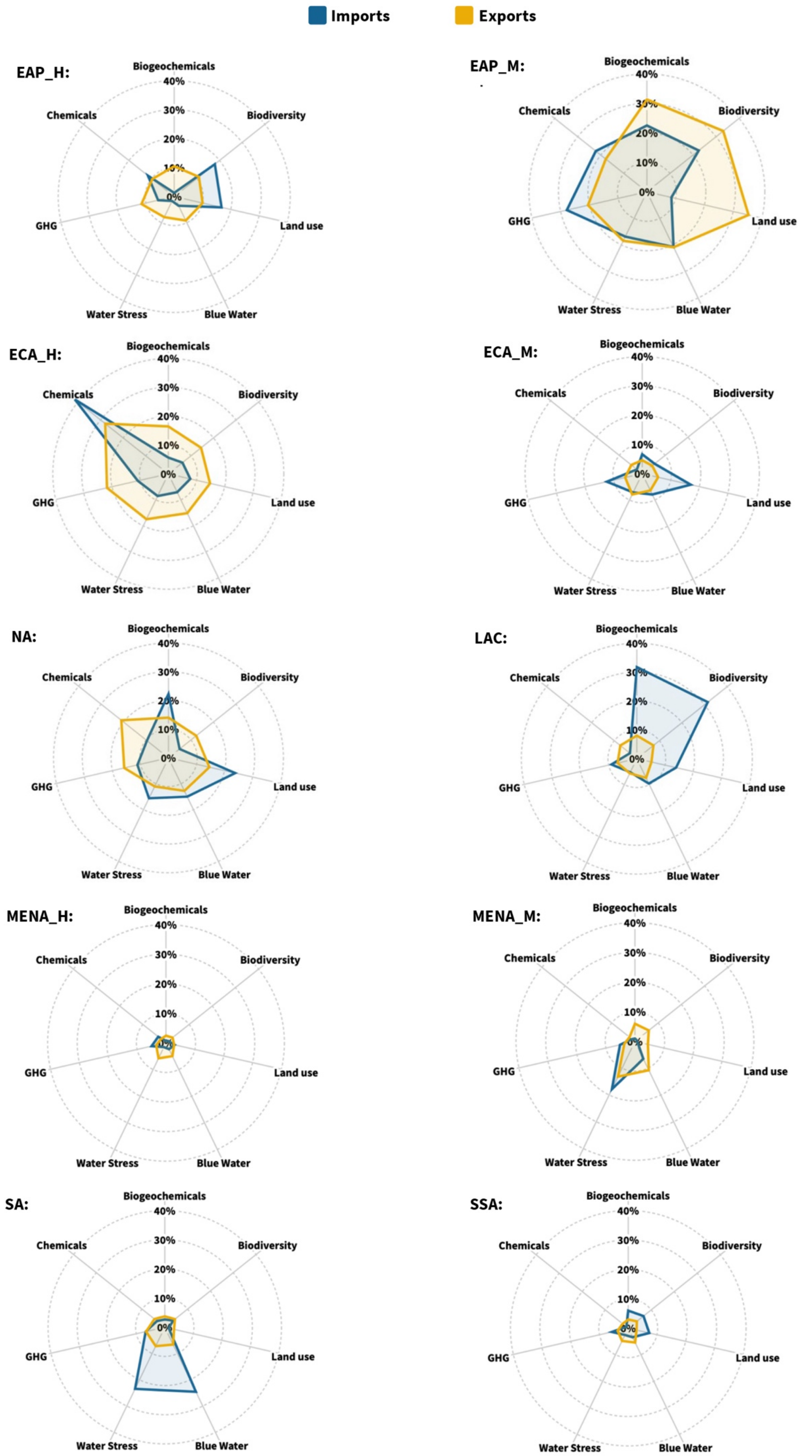

Figure 4: Share of pressure from import (consumption) and export (production) perspectives for selected regions. Note: EAP_H: High-income East Asia and Pacific, EAP_M: Middle- and low-income East Asia and Pacific, ECA_H: High-income Europe and Central Asia, ECA_M: Middle- and low-income Europe and Central Asia, SA: South Asia, SSA: Sub-Saharan Africa, MENA_H: High-income Middle East and North Africa, MENA_M: Middle- and low-income Middle East and North Africa, NA: North America, LAC: Latin America and the Caribbean. **Source:** GLORIA environmental extended multi-regional input-output database.

Each boundary pressure is driven by a different set of economic sectors. While some are relatively similar such as the boundaries of change in biosphere integrity and land system change, others such as novel entities and climate change are affected by very different economic activities. Consequently, the geographical distribution of the ecological pressure caused by global trade follows countries' sectoral import and export profiles. Import and export profiles are considered as good proxies for measuring countries' development levels, as exporting more complex manufacturing products is associated with higher levels of economic development whereas developing countries are usually more specialized in exporting primary and less complex products, particularly agricultural ones[41,42,43].

The group of Sub-Saharian African countries occupies a completely marginal position in the analysis, not importing or exporting relevant shares of the global pressure on the boundaries. Moreover, few countries such as Brazil and India lead exporting pressure numbers for other marginal groups of countries such as of middle- and low-income Latin America and the Caribbean, and of South Asia. In the end, import consumption pressure stems from high-income countries and in particular developing Asian countries demanding manufacturing and agricultural products from other regions, generating geographically localized pressure over the Earth system's processes.

To sum up, the pressure over the different planetary boundaries is sectoral specific and geographically specific, reflecting the international division of labour and matching the distribution of roles in international trade between developed and developing countries. By casting a light on the geographical and sectoral particularities of the pressure generated by global trade affecting each planetary boundary, this study provides valuable information for devising and tailoring more precise policies for the ecological transformation. On the productive side, effective transition policies should target precise sectors in specific places. On the consumption side, policies should incentivize more sober patterns of consumption that would reduce the import consumption pressure that drives the pressure on the boundaries.

As export production and import consumption are only different sides of the same global trade coin, it is important for these policies to be part of a global coordinated effort in which development, global trade and ecological issues are addressed together[44]. This does not mean that reducing international trade is a path for faster ecological transformation, as this study does not provide any comparison between domestic and international value chains on their ecological pressures. However, our results show that a significant share of the global pressure over the planetary boundaries happens due to the international value chains and the existing patterns of trade between countries. As such, it is important to put the ecological transformation at the core of international trade arrangements and move ahead of the current World Trade Organization's deadlock, as well as incorporate the ecological agenda in the negotiations of regional trade agreements.

METHODOLOGY

Estimating the pressure over each boundary

The pressure over each boundary is estimated with a Multi-Regional Input-Output model (MRIO), a kind of model that is able to measure international trade through consumption-based accounting. Countries are treated separately and in groups, depending on the boundary under consideration. The countries are treated individually and grouped according to their income level and region following World Bank's official classifications.

The matrix of total footprints embodied in final demand by country ($\mathbf{e^F}$) is given by

$$\mathbf{e^F} = \hat{\mathbf{e}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{F} \quad \textbf{(1)}$$

where $\mathbf{e}$ is the vector of planetary boundaries footprints per output by country and product, the hat indicates a diagonal vector, $\mathbf{A}$ is the matrix of technical coefficients and is $\mathbf{F}$ the matrix of final demand (lines are products and countries, and columns, countries and final demand components.

To obtain the footprints embodied in trade, we have to calculate the footprints embodied in imported final demand ($\mathbf{e^{FM}}$) and the footprints of imported inputs embodied in domestic final demand ($\mathbf{e^{ML}}$). However, to do this, we first have to calculate the domestic footprints embodied in imported final demand ($\mathbf{e^{DM}}$):

$$\mathbf{e^{DM}} = \hat{\mathbf{e}}[(\mathbf{I} - \mathbf{A})^{-1} \oslash \mathbf{ID}](\mathbf{F} \oslash \mathbf{IF}) \quad \textbf{(2)}$$

where $\mathbf{IF}$ is a matrix with the same dimension as $\mathbf{F}$ but with zero for domestic relations and one for trade across countries, $\mathbf{ID}$ is a matrix with the same dimension as $\mathbf{A}$ but with zero for domestic relations and one for trade across countries, and $\emptyset$ is the element-wise multiplication.

We can then obtain planetary boundaries footprints embodied in trade first excluding the domestic final demand from equation (1), which gives footprints embodied in imported final demand ($\mathbf{e^{FM}}$), and then excluding the domestic inputs from the same equation, which gives footprints embodied in inputs ($\mathbf{e^{ML}}$):

$$\mathbf{e^{MF}} = \hat{\mathbf{e}}(\mathbf{I} - \mathbf{A})^{-1}(\mathbf{F} \emptyset \mathbf{IF}) - \mathbf{e^{DM}} \quad \textbf{(3)}$$

and

$$\mathbf{e^{ML}} = \hat{\mathbf{e}}[(\mathbf{I} - \mathbf{A})^{-1} \emptyset \mathbf{ID}]\mathbf{F} - \mathbf{e^{DM}} \quad \textbf{(4)}$$

Note that in both resulting matrices, the domestic interrelations have the same value and they account for domestic inputs embodied in imported final demand. This is why one need to exclude $\mathbf{e^{DM}}$ from them.

We can therefore obtain footprints related to trade as

$$\mathbf{e^{tr}} = \mathbf{e^{MF}} + \mathbf{e^{ML}} + \mathbf{e^{DM}} \quad \textbf{(5)}$$

and imported footprints embodied in countries' final demand as

$$\mathbf{e^{M}} = \mathbf{e^{MF}} + \mathbf{e^{ML}} \quad \textbf{(6)}$$

This gives us a matrix of country by product in the rows and country by component of final demand in columns. The countries (and products) in rows are the origin of the footprint, and the countries (and final demand component) in columns are the consumer of these footprints.

It is also possible to understand this by dividing the goods in the MRIO table into four groups. Each good can be traded during its production (yes or no) and/or can be traded when purchased for final consumption (yes or no). Avoiding double counting, Table 3 shows the equation to calculate the pressure exerted by each group of goods.

Interindustry matrix	**Final demand**	**Was it traded internationally?**	**Equation**
Domestic	Domestic	No	$e = e^{MF} - e^{ML} - e^{DM}$

Domestic	Imported	Yes	$e^{MF} = \hat{e}(I - A)^{-1}(F \emptyset IF) - e^{DM}$
Imported	Domestic	Yes	$e^{ML} = \hat{e}[(I - A)^{-1} \emptyset ID]F - e^{DM}$
Imported	Imported	Yes	$e^{DM} = \hat{e}[(I - A)^{-1} \emptyset ID](F \emptyset IF)$

Table 3: Trade pressure exerted by the four groups of goods in the MRIO matrix

One can also calculate a similar matrix but with products rather than countries in columns, which gives us the embodied footprints by country and product of origin in rows and consumed product in columns:

$$\mathbf{e^{Mi}} = \mathbf{\hat{e}(I - A)^{-1}\widehat{f^{M}}} + \mathbf{\hat{e}[(I - A)^{-1} \emptyset ID]\hat{f}} - \mathbf{2\hat{e}[(I - A)^{-1} \emptyset ID]\widehat{f^{M}}} \qquad (7)$$

where $\mathbf{f} = \mathbf{F\iota}$ is a vector of total final demand, $\mathbf{f^M} = (\mathbf{F} \emptyset \mathbf{IF})\boldsymbol{\iota}$ is a vector of imported final demand, and $\boldsymbol{\iota}$ is a vector of ones to sum-up the columns of final demand.

We apply this method to each pre-calculated variable related to boundaries replacing $\mathbf{e}$ for the specific footprint intensity. In the case of GHG emissions, it is provided directly by GLORIA environmental MRIO, and we only need to obtain the intensity dividing by output. In the case of land use, biodiversity loss, water stress, blue water consumption, material use and energy, one need to first aggregate the different sources, and then divide by output to obtain the intensity.

In the case of fertilizers embodied in agriculture production, we calculate the total fertilizers embodied in production ($\mathbf{q^{f,t}}$),

$$\mathbf{q^{f,t}} = \mathbf{\widehat{q^{f}}(I - A)^{-1}} \qquad (8)$$

where $\mathbf{q^f}$ is the sum of fertilizers divided by output, and then we exclude the non-agriculture sectors, setting their values to zero.

Finally, in the case of chemicals, we calculate the total material embodied in chemical production, excluding the material transformed into energy ($\mathbf{q^{m,t}}$), as follows:

$$\mathbf{q^{m,t}} = \mathbf{\widehat{q^{m}}[(I - A)^{-1} \emptyset \,(1 - IE)]} \qquad (9)$$

where $\mathbf{q^m}$ is the sum of materials divided by output and $\mathbf{IE}$ is a matrix with energy rows set to one and others set to zero, and then we exclude the non-chemical sectors, setting their values to zero.

Data Sources

The ecological footprints embodied in trade relations were calculated using data from the GLORIA environmental extended multi-regional input-output (MRIO) database[45] constructed in the Global MRIO Lab[46], which accounts for 164 countries and 120 sectors.

Limitations

One of the main caveats of input-output analysis consists of the linear assumption of the model which assumes that all inputs are employed in fixed proportions, hiding scale effects[42]. This is an important issue to be addressed in further studies looking at particular sectors pressuring the boundaries, as pressure might scale differently for each sector. Nevertheless, the linear proportionality assumption is usually assumed in the literature to be the best method available for estimating environmental footprints[47,48].

Another limitation is the low spatial resolution of the model which reduces the accuracy of the variables' values, particularly in large countries. This might be extremely relevant for some boundaries such as change in biosphere integrity, given that multiple biomes and natural characteristics may exist inside the same country.

Moreover, this study is not able to assess important synergies among the boundaries. For instance, the effects of the increasing pressure on the climate change boundary may lead to rising pressure over the freshwater change boundary due to regional climate modifications affecting the water cycle. Tipping points are inter-related to each other.

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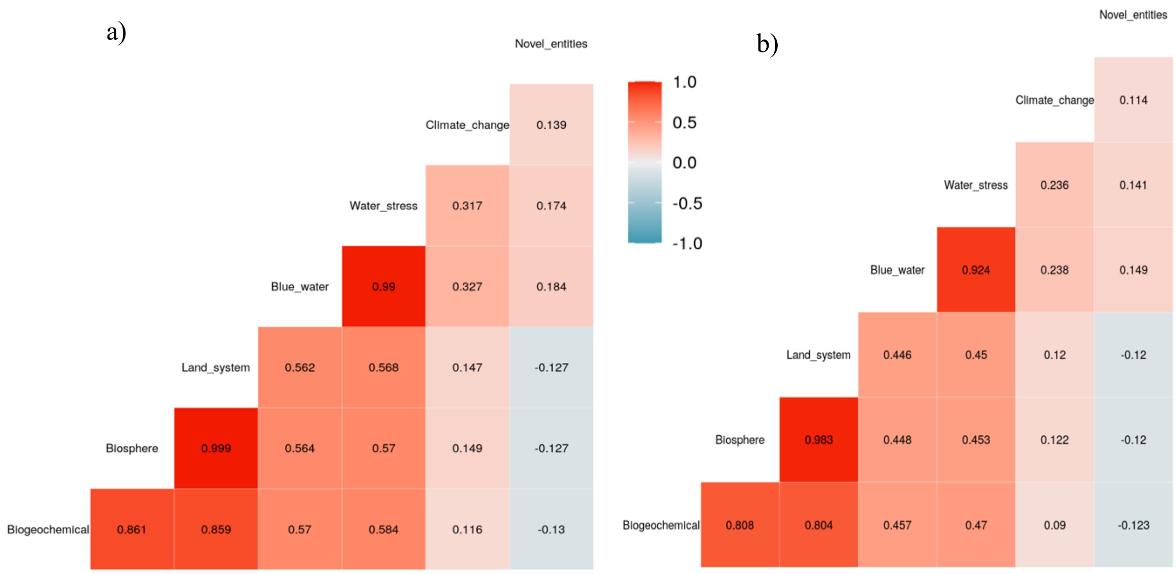
ANNEX A

Correlation, cluster and PCA analysis from production perspective

For both the correlation and cluster/PCA analysis the data employed is the share of total pressure each economic sector per boundary from the production perspective. Therefore, the sectors with higher pressuring shares are the ones that directly pressure the boundaries when producing. All the seven variables employed in the study up to now are used. Given that the data is not normally distributed nor homoscedastic, the correlation analysis is carried out using the Spearman Rank and the Kendall Tau correlation methods.

Figure A.1: Correlation matrix of the sectoral pressure exerted over each boundary from production perspective using (a) Spearman Rank and (b) Kendall Tau correlation



The hierarchical cluster analysis is first calculated using Euclidean distances and then clustered following 4 different techniques: single link, average link, Ward.D and Ward.D2. The number of clusters for each method is decided based on a qualitative assessment of dendrogram analysis. The final results presented in the discussion section of the paper consist of a qualitative interpretation of the results of the four clustering methods. The cluster results (Figure A.2) are plotted with the help of a principal component analysis (PCA). The two most significant components are employed in the y and x axis. In Figure A.3 we show the contributions of each variable in the components employed in the cluster figures.

Figure A.2: Cluster plots of sectoral pressure using different methods: (a) Single link, (b) Average link, (c) Ward.D and (d) Ward.D2

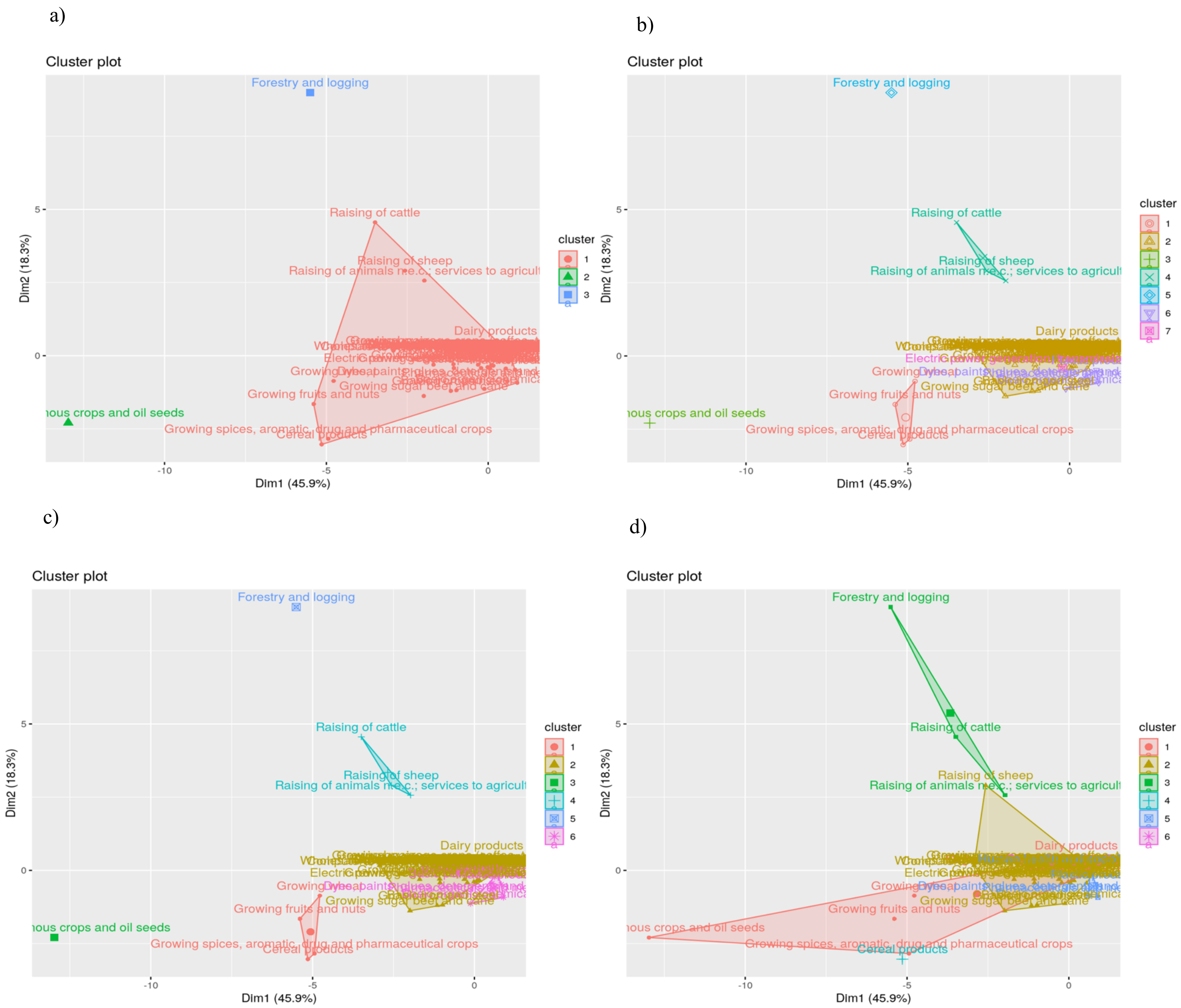
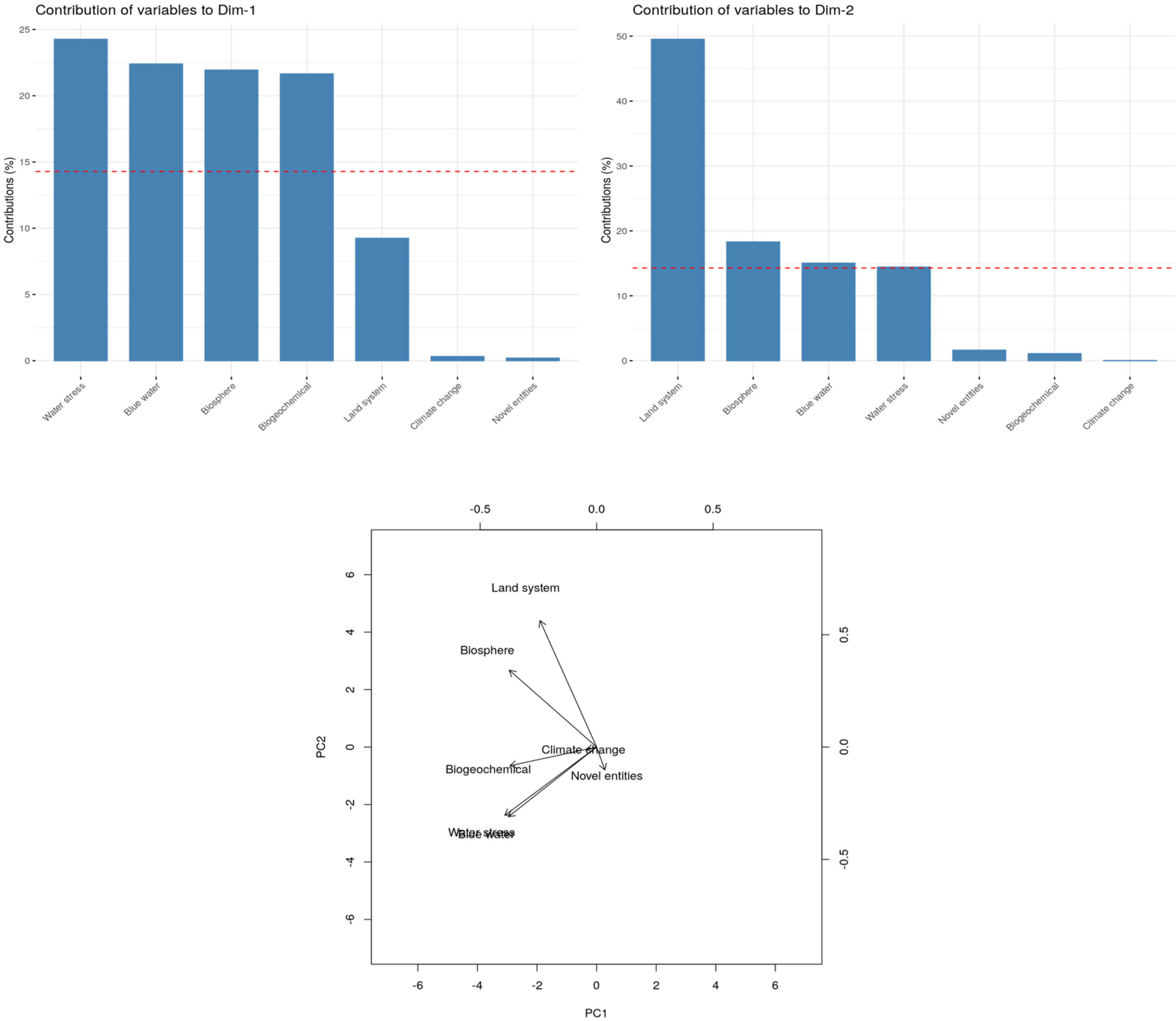


Figure A.3: Contribution of different variables for the PCA analysis upholding the cluster plots

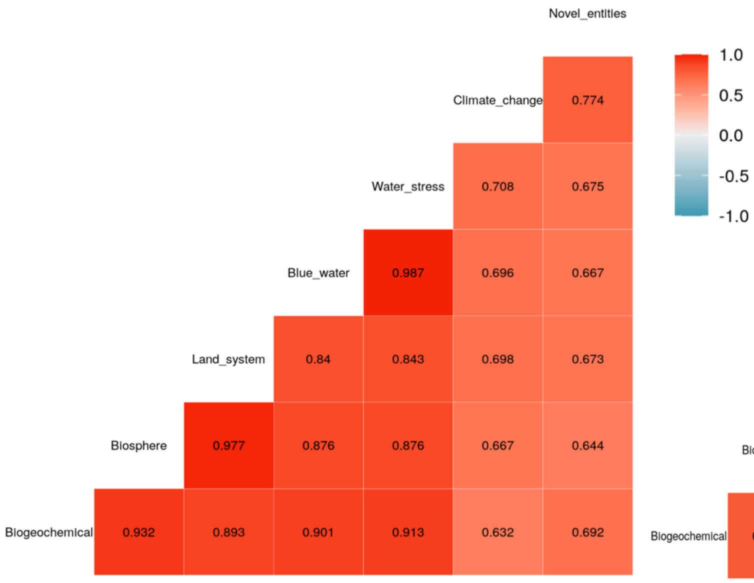


Correlation, cluster and PCA analysis from consumption perspective

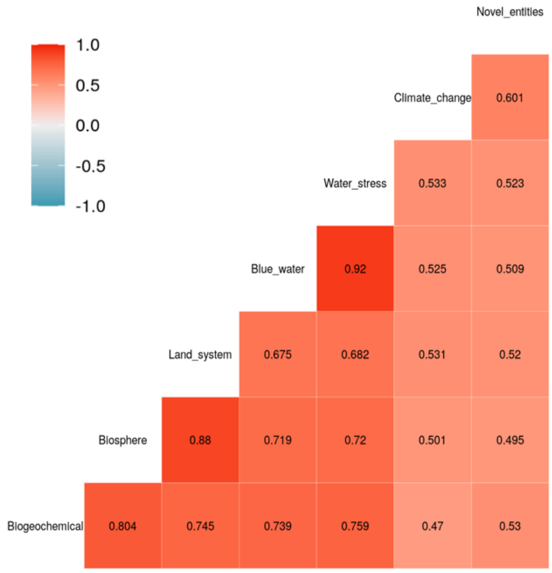
For both the correlation and cluster/PCA analysis from the consumption perspective the data employed is the share of indirect total pressure each economic sector per boundary. In other words, it's the pressure generated in the effort of the economic system to satisfy the demand of each sector, being it intermediary import consumption or final import consumption. Figure A.4 displays the correlation matrices.

Figure A.4: Correlation matrix of the sectoral pressure exerted over each boundary from consumption perspective using (a) Spearman Rank and (b) Kendall Tau correlation

a)



b)



The hierarchical cluster analysis with data from consumption perspective is calculated in a complete similar way.It is first calculated using Euclidean distances and then clustered following 4 different techniques: single link, average link, Ward.D and Ward.D2. The number of clusters for each method is also decided based on a qualitative assessment of dendrogram analysis. The results presented in the discussion section of the paper consist of a qualitative interpretation of the results of the four clustering methods. The cluster results (Figure A.5) are plotted with the help of a principal component analysis (PCA). The two most significant components are employed in the y and x axis. In Figure A.6 we show the contributions of each variable in the components employed in the cluster figures.

Figure A.5: Cluster plots of sectoral pressure using different methods: (a) Single link, (b) Average link, (c) Ward.D and (d) Ward.D2

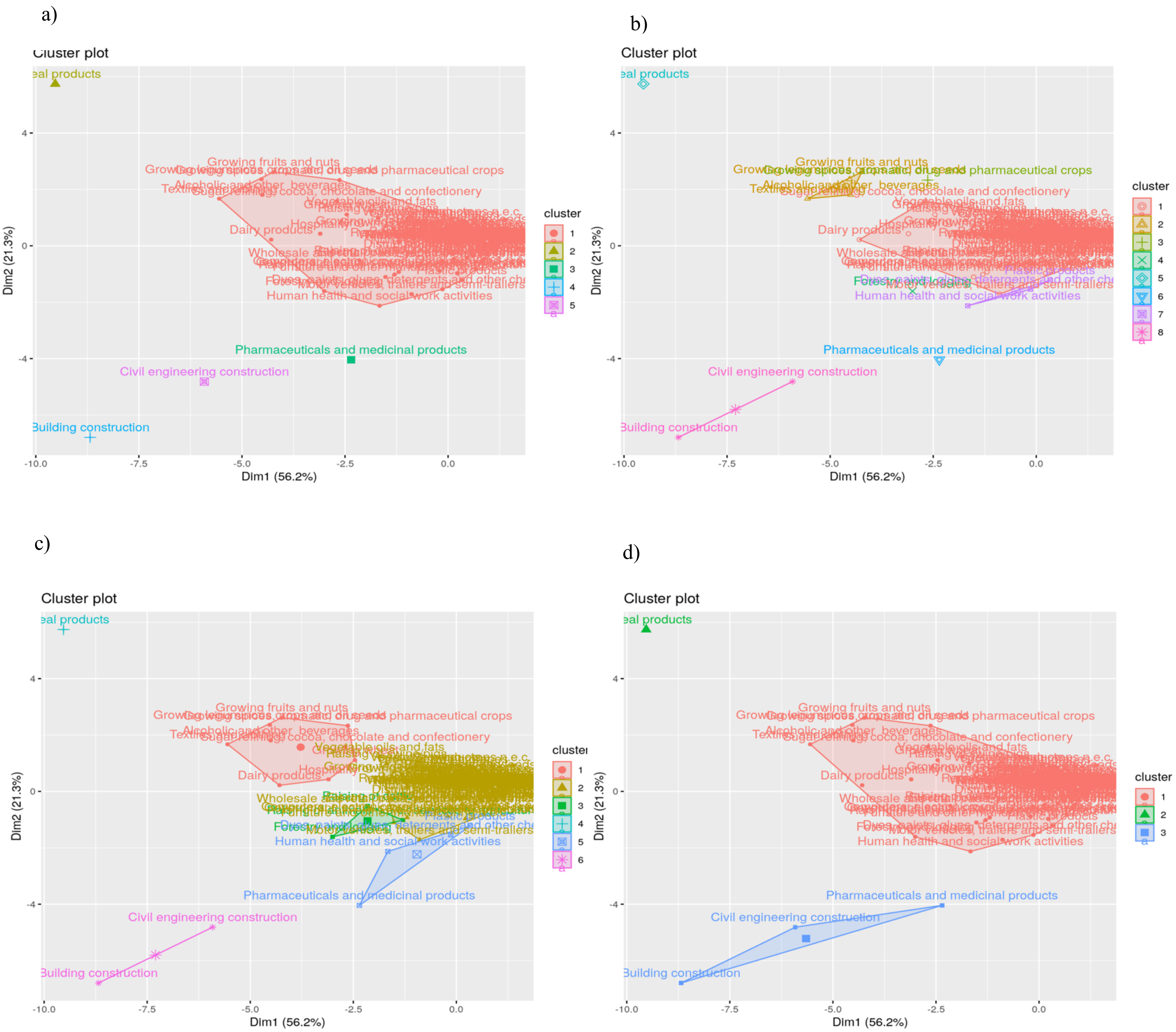


Figure A.6: Contribution of different variables for the PCA analysis upholding the cluster plots