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Analysis

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Ecologically unequal exchanges driven by EU consumption

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In our globalized economy, the consumption of goods and services induces economic benefits but also environmental pressures and impacts around the world. Consumption levels are especially high in the current 27 member countries of the European Union (EU), which are some of the wealthiest economies in the world. Here, we determine the global distribution of ten selected environmental pressures and impacts, as well as value added induced by EU consumption from 1995 to 2019. We show that large shares of all analysed environmental pressures and impacts are outsourced to countries and regions outside the EU, while more than 85% of the economic benefits stay within the member countries. But there is also uneven distribution of costs and benefits within the EU. Over the analysed period, pressures and impacts induced by EU consumption largely decreased within the EU but increased outside its borders. We show that Eastern European neighbours of the EU experienced the highest environmental pressures and impacts per unit of GDP associated with EU consumption. The findings of this research add to the discussions on outsourcing environmental pressures and impacts and highlight the need for a reduction of pressures and impacts induced by EU consumption.

Consumption of goods and services is fuelling the global economy but it is also linked to a wide variety of environmental pressures, such as land use or emissions, and in turn impacts on human health and ecosystems. The steep increase of human consumption over the last decades is putting our planet and our environment under growing pressure. Already today, human consumption is transgressing many of the boundaries of our planet[1]. But neither consumption of goods and services nor the associated environmental pressures and impacts are equally distributed across the globe. Consumption is closely linked to wealth and income. Simply put, the more money one has available the higher the expenditure and thus consumption. However, the global distribution of wealth and income is extremely unequal, with large amounts of money concentrated in a few rich countries[2]. Many of these countries are situated in Europe and are amongst the current 27 members of the European Union (EU), including Croatia and excluding the United Kingdom. Previous studies have highlighted the disproportionally large environmental pressures and impacts associated with consumption in Europe and more specifically in the EU[3–5]. These consumption-based environmental pressures and impacts are often quantified as footprints by attributing environmental pressures and impacts caused during the life of a product or service to their consumers. EU member states have some of the world's highest per capita consumption-based footprints

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for carbon emissions[3,5–7], land use[3,5,8], material consumption[3,5], water consumption[3,5] or biodiversity loss[9]. To stay within a safe operating space on the planet, environmental pressures and impacts from EU consumption need to decrease substantially[10].

While existing literature established total footprints associated with consumption in European countries for multiple indicators and identified products related to high impacts and pressures[11], there are few studies which look at the geographical distribution of these environmental pressures and impacts[12,13]. However, as EU consumption is not only having notable effects on the local environment but is causing pressures and impacts across the world, it is paramount to identify where these pressures and impacts are happening and how they have developed in recent years of increased environmental crises.

To give an unprecedentedly comprehensive overview on the wide variety of environmental pressures and impacts associated with EU consumption, we determined the geographical distribution of ten selected pressures and impacts caused within and outside the current member states, using an environmentally extended multiregional input–output (EEMRIO) approach. Additionally, we quantified how they changed over time in the period 1995–2019 with data from the EXIOBASE v.3.8.1 database[14].

To represent the multiple dimensions of environmental impacts and pressures adequately, the selection of indicators is key. First, we chose indicators that were suggested by the European Commission to facilitate resource efficiency and track the impacts of EU consumption[15,16]. They include four widely used[3,5] pressures: greenhouse gas (GHG) emissions[6,7,17], material consumption[18,19], land use[8,20] and the consumption of surface and ground water or blue water consumption[13,21].

However, a recent study[16] highlighted that these four indicators alone, do not work well as proxies for the total multidimensional impact of human consumption. Thus, they provide a set of seven additional headline indicators, which explains 95% of the variance of environmental indicators in the EXIOBASE-EEMRIO database. Next to the GHG emissions, which are already included, they consist of particulate matter formation, freshwater aquatic ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, photochemical oxidation and land occupation damage to ecosystem quality, here quantified as biodiversity loss due to land coverage. Other environmental pressures or impacts, such as eutrophication or acidification are correlated with the chosen ten indicators and hence would add little to the analysis.

The EU's consumption is not only connected to environmental pressures and impacts across the world but also creates value added or gross domestic product (GDP), one of the main and most widely used economic indicators, along global supply chains. Previous research showed that, depending on the position in the supply chain, some countries experience little environmental pressures and impacts from consumption but gain substantial amounts of value added, while the opposite is true for others[22–24]. In this research we compare the geographical distribution of value added to the distribution of pressures and impacts associated with EU consumption to determine which countries and regions outside and inside the EU benefitted the most and which ones lost out.

Results

Geographical distribution of environmental pressures and impacts

The first key insight of this research is that the global distribution of environmental pressures and impacts connected with EU consumption varies notably by pressure and impact. While, for some indicators, pressures and impacts were induced mainly within the EU, others happened largely outside the union.

During the investigated time period, 66–77% of GHG emissions happened within the EU, while the remaining 23–34% happened outside its borders, as seen in Fig. 1. Similarly, 62–73% of material consumption associated with EU consumption happened within the 27 member states. By contrast, blue water consumption was consistently higher in countries outside the EU than those within. Land use and biodiversity loss from land use show roughly a 50–50 split with shares increasing in the EU throughout the analysed period. However, all other indicators show small but notable trends of increasing shares outside the EU. Nevertheless, trends for some indicators are not completely stable. In some years, freshwater aquatic ecotoxicity and terrestrial ecotoxicity associated with EU consumption were higher in the EU, while in other years the pressures outside the EU borders were higher than within.

The country or region with the highest shares of pressures or impacts connected to EU consumption changes with the pressure or impact category. While the largest share of land use was located in the rest-of-the-world (RoW) Africa region, with 10–18% each year, the highest shares of biodiversity loss from land use was consistently located in Spain, contributing 15–19% of the total biodiversity loss from land use induced by EU consumption. Spain also experienced the highest shares of blue water consumption in 2018 and 2019, while in the other years blue water consumption was higher in the RoW Asia and Pacific region (for 20 years) or the RoW Middle East region (for 3 years). Ecotoxic emissions to land, freshwater systems and the sea, were largest in Greece for most of the years and contributed 12–19% of all ecotoxic emissions associated with EU consumption. Germany and France experienced the largest share of particulate matter formation until 2004. Since then, particulate matter formation associated with EU consumption was highest in China (except for 2017, in which Germany has the largest value). The largest share of GHGs was consistently emitted in Germany with 15–19% of all GHG emissions connected to EU consumption. Photochemical oxidation was highest in Germany (11–16%). Similarly, EU consumption led to the highest shares of material consumption in Germany (10–16%). Figure 2 shows the geographical distribution of pressures and impacts in 2019.

Within the EU, blue water consumption and biodiversity loss from land use were highest in Spain, as seen in Fig. 2. France and Spain also show the highest share of land use from EU consumption, next to Sweden, Germany and Poland. Beside Greece, ecotoxic emissions were high in Germany, Italy, Cyprus and Romania. The most populous countries of the EU (Germany, France, Italy, Poland and Spain) experienced the highest GHG emissions, particulate matter formation, photochemical oxidation and the largest material consumption associated with EU consumption throughout the analysed period. Particulate matter formation was also high in Greece.

To understand the contribution of different consumption items to environmental pressures and impacts induced by EU-27 consumption, we grouped them into six consumption categories: food, clothing, mobility, services, manufactured products and shelter. Outside the EU-27, consumption of food was the highest contributor to land use and biodiversity loss from land use and induced >50% of blue water consumption. Meanwhile consumption of mobility and manufactured products induced the largest amount of ecotoxicity, photochemical oxidation, GHG emissions and particulate matter formation. Inside the EU-27, food consumption dominated land use, biodiversity loss from land use and blue water consumption even more than outside the EU-27, contributing substantially more than half of the pressures and impacts in the last two categories. Similarly, mobility was often connected to >40% of the ecotoxicity pressures from all EU-27 consumption within the union. GHGs emitted associated with EU-27 consumption within the EU-27 were mostly induced by consumption connected to shelter, services and food. However, while outside EU-27 consumption of clothing contributed 4–8% to categories such as GHG emissions and particulate matter formation induced by EU-27 consumption, it never contributed >2% to any of the analysed pressures and impacts within the EU-27.

Evolution of environmental pressures and impacts of EU consumption

The second key insight shows that five out of ten environmental pressures and impacts induced by EU's consumption decreased between

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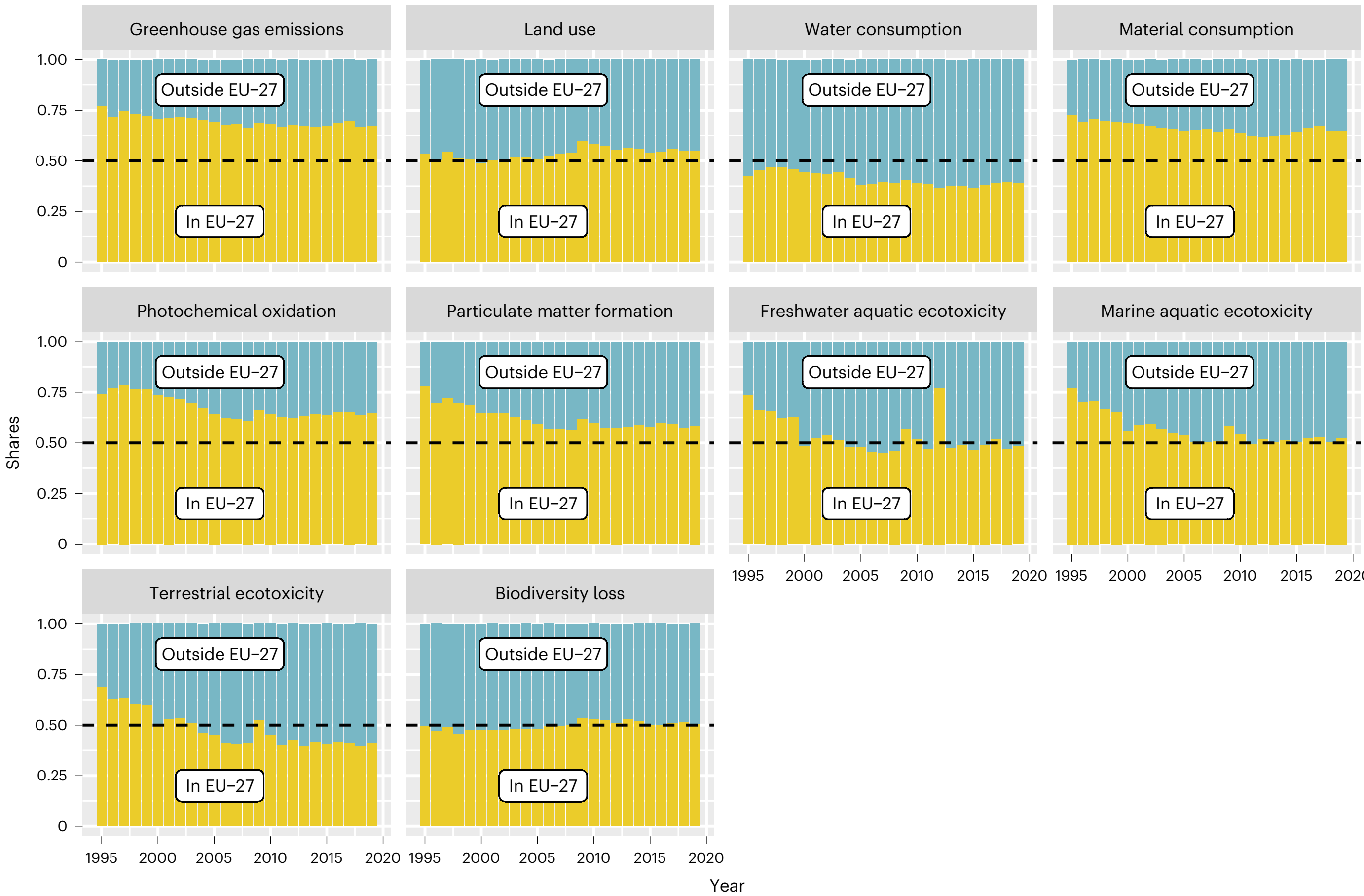

Fig. 1 | Relative distribution of pressures and impacts associated with EU-27 consumption inside and outside of the EU-27 in 2019. The ecotoxicity results from EXIOBASE dataset have to be seen as lower bounds.

1995 and 2019. Marine aquatic ecotoxicity and particulate matter formation showed the largest drop of −17.5% and −14.4%, respectively, as seen in Fig. 3. Other indicators, such as GHG emissions (−4.1%), land use (−5.5%) and biodiversity loss from land use (−8.8%), declined to a lesser extent. Meanwhile, the other five indicators increased during the analysed period: material footprint (+9.4%), terrestrial ecotoxicity (+28.3%), blue water consumption (+18.9%), photochemical oxidation (+1.5%) and freshwater aquatic ecotoxicity (+6.6%). While most of the environmental pressures and impacts connected to EU-27 consumption of food, services and shelter decreased, 2019 often saw higher pressures and impacts related to the consumption of clothing and manufactured products than 1995.

Associated pressures and impacts within the EU show a different trend. All pressures and impacts dropped, except for blue water consumption (+9.4%). Within the EU, marine aquatic ecotoxicity almost halved between 1995 and 2019. In contrast, environmental pressures and impacts induced by EU consumption outside the EU largely rose at the start of the twenty-first century, except for decreases in total land use (−8.6%) and biodiversity loss from land use (−10.9%). Most notably, terrestrial ecotoxicity and freshwater aquatic ecotoxicity pressures outside the EU rose by +142.8% and +105.7%, respectively. Hence, the EU was able to decrease environmental pressures and impacts connected to local consumption within its borders, while increasing pressures and impacts outside its borders.

Environmental pressures and impacts also rose in some EU member states. In Cyprus, marine aquatic ecotoxicity, freshwater aquatic ecotoxicity and terrestrial ecotoxicity rose by multiple hundred per cent from 1995 to 2019, as seen in Extended Data Fig. 1. Cyprus also saw increases in particulate matter formation, GHG emissions, photochemical oxidation, land use and material consumption. Moreover, Ireland experienced a rise in all analysed environmental indicators, except for GHG emissions. Nevertheless, pressures and impacts induced by EU consumption dropped in most of its member states. For two (the Netherlands and Sweden) pressures and impacts in all ten categories dropped from 1995 to 2019. Furthermore, many member states, such as Austria, Czechia, Italy, Poland, Romania and Slovenia, saw decreases in nine of ten analysed environmental pressures and impacts. Environmental pressures and impacts induced by EU consumption not only decreased within the union but also abroad. For example, the United States and Canada experienced less environmental pressures and impacts in all ten categories in 2019 than in 1995. Furthermore, all impacts and pressures, except for those related to ecotoxicity, declined in the RoW America region. In contrast, all analysed impacts and pressures associated with EU consumption increased in Brazil, China, India and Japan, as well as in the RoW Europe and the RoW Middle East regions.

Most unbeneficial EV-ratios for EU neighbours

To gain further insights into the effects of EU consumption in different countries and regions, we quantified economic benefits as value added or GDP associated with EU consumption inside and outside the union and compared it with the associated environmental pressures and impacts. Except for the financial crisis in 2008, value added associated with the production of EU consumption increased from €6.2 trillion in 1995 to €13.4 trillion in 2019. In the analysed period, 86–91% of the generated value added stayed within the EU. Within the EU, consumption connected to services and shelter contributed more than 43% and 23%, respectively, to the overall value added by EU consumption.

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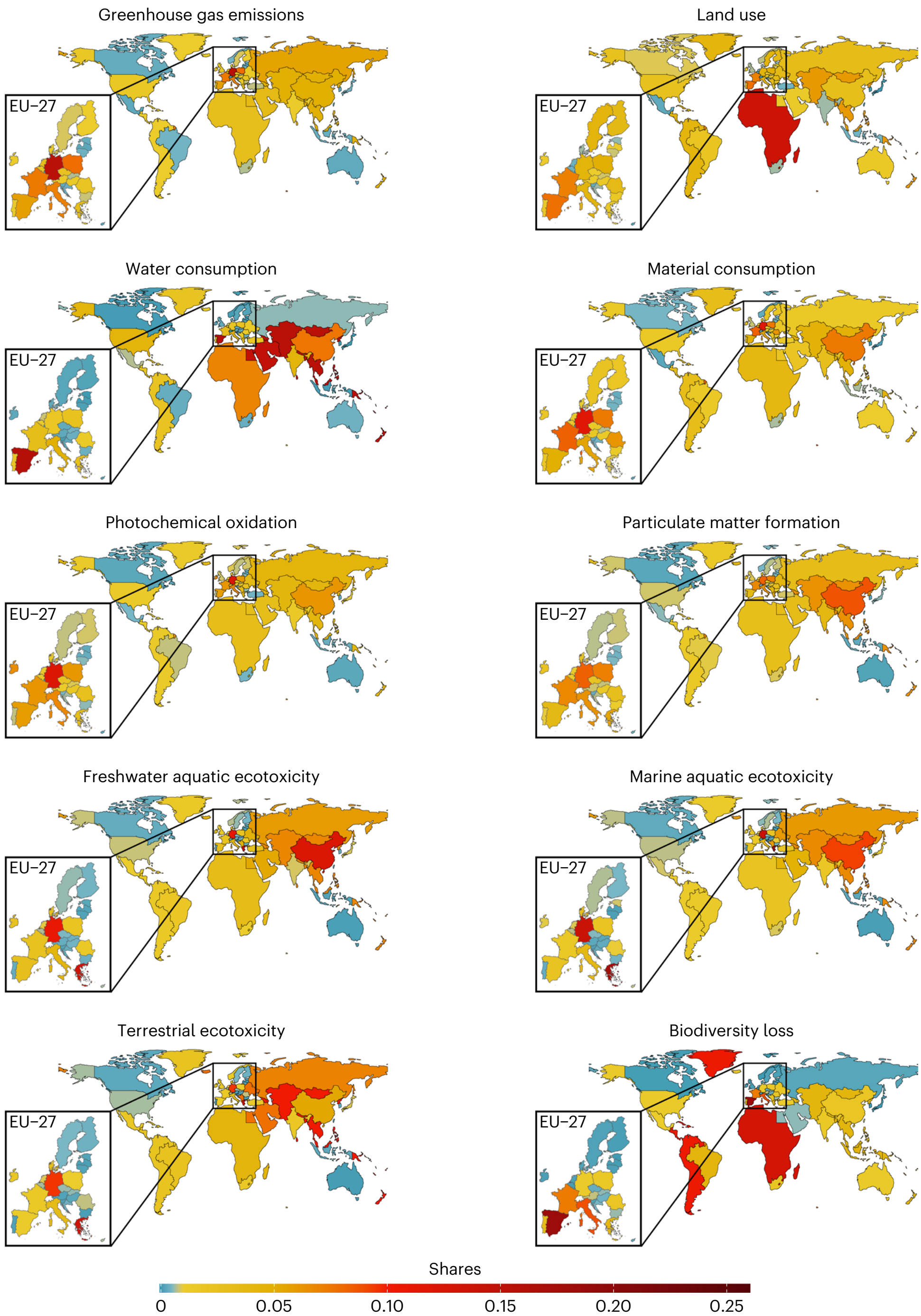

Fig. 2 | Relative distribution of pressures and impacts associated with EU-27 consumption in 2019. Pressures and impacts within EU-27 countries are highlighted in an extra panel in the bottom left of each map. The ecotoxicity results from EXIOBASE dataset have to be seen as lower bounds.

In contrast, consumption of services, manufactured products and mobility were the main contributors to value added associated with EU consumption outside the EU.

At the country and region levels, the most populous EU member states, Germany, France, Italy and Spain, also experienced the highest share of value added. Together they received more than 60% of the value added by EU consumption in the late 1990s and still received 56.3% in 2019, as seen in Fig. 4. Meanwhile, outside the EU, the United States (1.9–3.3%), the United Kingdom (1.1–1.7%) and China (0.1–1.7%) are the countries which received the highest shares of value added from EU's consumption.

To compare the shares of value added and environmental pressures and impacts induced by EU consumption we use the emissions-to-value-added-ratio (EV-ratio)[23] by dividing the share of global pressure or impact by the share of global value added in a region or country. A value <1 indicates that the share of economic benefits was higher than the share of environmental pressure or impact received from a country's contribution to global value chains while a value >1 indicates that a country receives a larger share of environmental damages than its share of economic benefits.

Together, the EU experienced EV-ratios <1 for all ten analysed indicators in every year between 1995 and 2019. Conversely, aggregating

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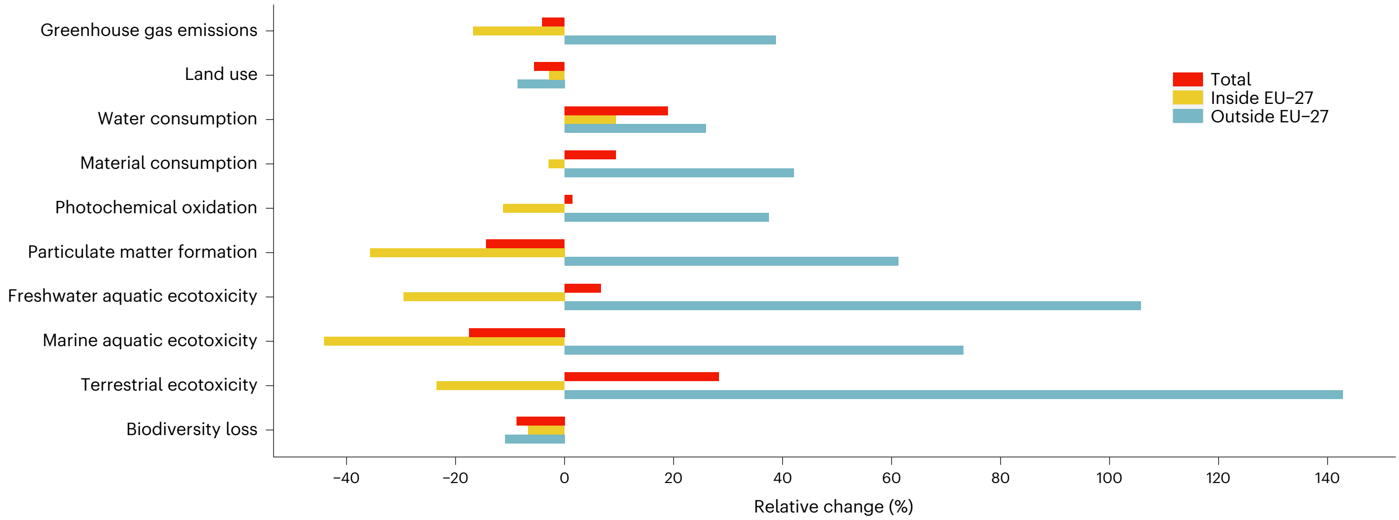

Fig. 3 | Relative change of pressures and impacts associated with EU-27 consumption between 1995 and 2019 inside the EU-27, outside the EU-27 and in total. The ecotoxicity results from EXIOBASE dataset have to be seen as lower bounds.

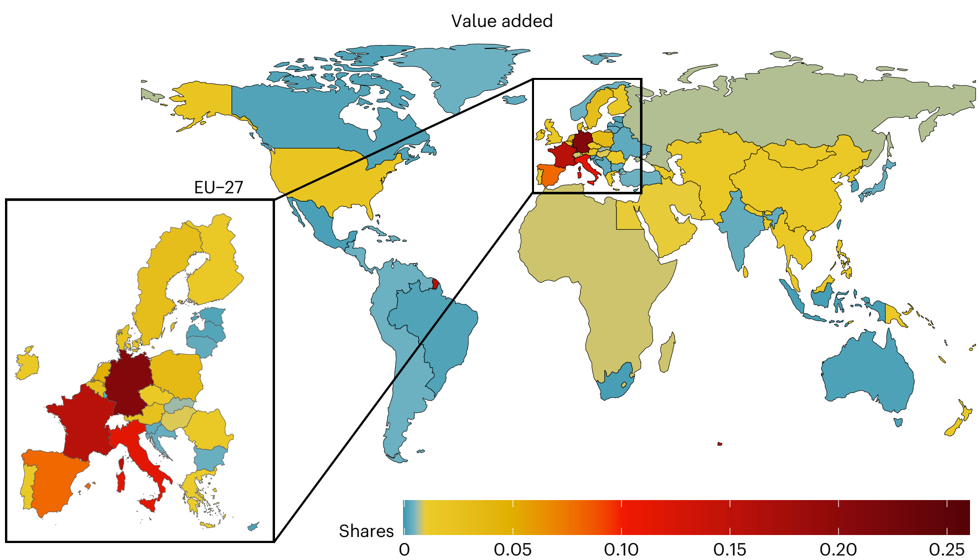

Fig. 4 | Relative distribution of value added associated with EU-27 consumption in 2019. Relative distribution within EU-27 countries are highlighted in an extra panel in the bottom left of the map.

all countries and regions outside the EU to the RoW, it consistently experienced EV-ratios >1. As EV-ratios for blue water consumption, freshwater aquatic ecotoxicity, terrestrial ecotoxicity, land use and biodiversity loss from land use were lowest in the EU, mostly between 0.4 and 0.6, they were highest in the RoW region with values between 1.6 and 6 throughout the years. In other words, in the RoW region, shares of these five indicators linked to EU consumption were up to six times higher than their respective global shares of value added in these years. For other indicators, such as GHG emissions or photochemical oxidation, the distribution between the EU countries and the RoW region was closer to the distribution of value added, resulting in EV-ratios closer to 1.

Taking a closer look at individual countries and regions reveals even larger differences in EV-ratios, as seen for 2019 in Fig. 5 and for 1995 in Supplementary Fig. 1. In 2019, very low EV-ratios were experienced; for example, for biodiversity loss from land use in the Benelux countries, indicating that value added shares of EU consumption were >30 times higher than impact shares. However, also countries outside the EU, such as South Korea (0.02), Norway (0.04) or the United Kingdom (0.05) experienced low EV-ratios for biodiversity loss from land use. In contrast, the highest EV-ratios in 2019 were found for biodiversity loss from land use in Indonesia (50.85) or Brazil (27.09). This shows that the geographical distribution of biodiversity loss from land use induced by EU consumption does not follow the same pattern as the value added distribution. In a similar manner, EV-ratios of blue water consumption connected to EU household consumption showed very small values in some countries, such as Luxembourg (0.03) or Switzerland (0.04) and very high ones in others, such as India (14.27) or the RoW Middle East region (14.97). The geographical distribution of GHG emissions and photochemical oxidation associated with EU consumption is closer to the distribution of value added, resulting in less diverging EV-ratios for the analysed countries and regions.

Looking at the big picture, by including EV-ratios for all ten indicators and computing an average EV-ratio per country or region per

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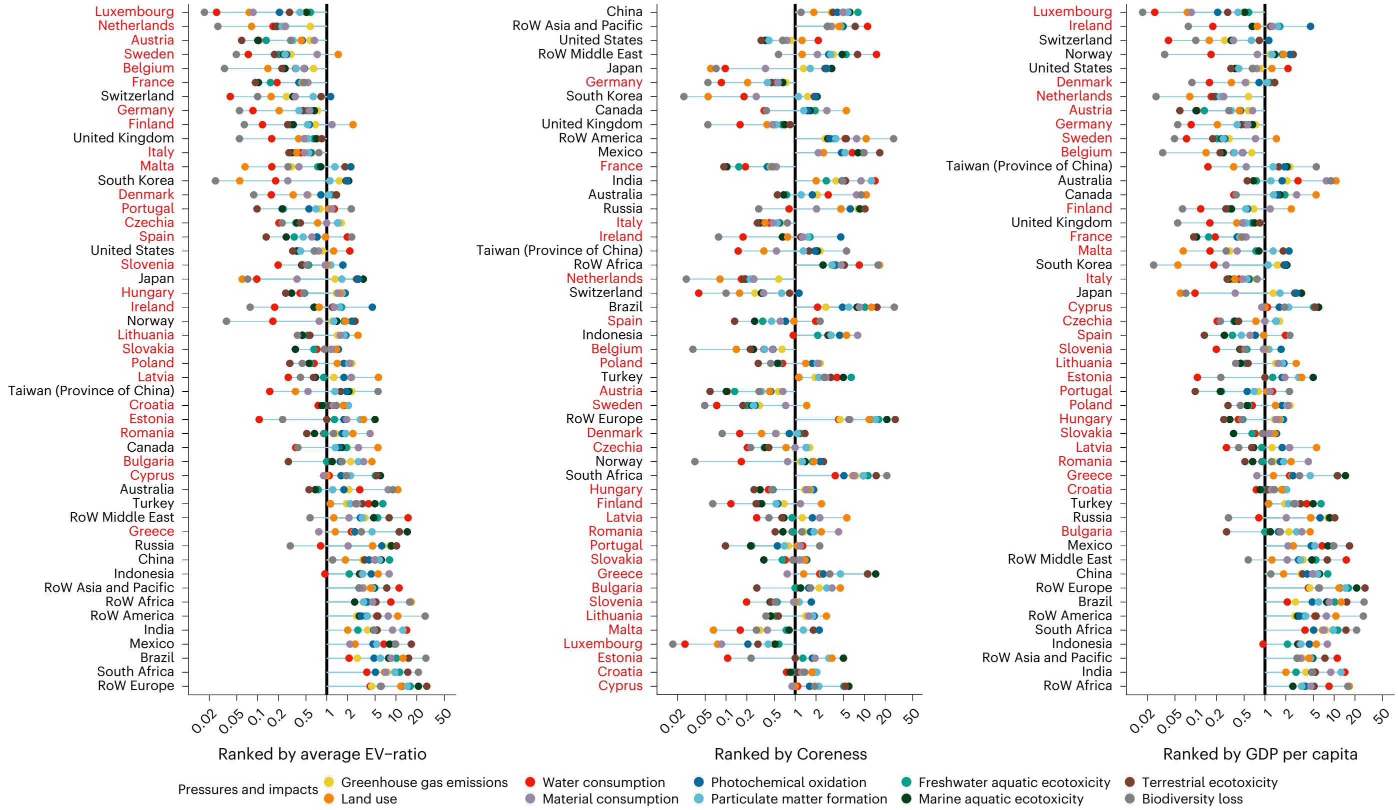

Fig. 5 | EV-ratios in 2019 for pressures and impacts associated with EU-27 consumption. Countries/regions are ranked by average EV-ratio, Coreness and GDPpc. EV-ratios for different pressure and impact categories associated with EU-27 consumption are shown in the colour key. EU-27 countries are coloured red, while countries and regions in the rest of the world are coloured black.

year, we see that EU member states, such as the Benelux countries and Austria, experienced the lowest values over the years (results for 2019 in Fig. 5, left ranking) corresponding with the lowest environmental pressures and impacts per unit of value added from EU consumption. Meanwhile, the RoW Europe region, encompassing countries such as Ukraine and the Western Balkans, consistently ranked as the region with the highest average EV-ratios, in other words receiving the lowest share of value added or GDP in comparison to the environmental pressures and impacts associated with EU consumption. Moreover, in 2019 the region had the highest EV-ratios for all ecotoxicity indicators, particulate matter formation (14.5) and photochemical oxidation (12.2) of all countries and regions.

Some countries outside the EU, such as Switzerland, the United Kingdom and the United States, experienced even lower average EV-ratios than member states throughout the years. Nevertheless, in most countries and regions shares of environmental pressures and impacts were substantially higher than shares of value added, resulting in high EV-ratios. Despite being the region with the highest average EV-ratio in every year except for 2012, the RoW Europe region also experienced the largest decline, followed by Russia and Indonesia. While these countries and regions still experienced amongst the highest environmental pressures and impacts per value added associated with EU consumption, their EV-ratios became more beneficial for them throughout the analysed period. The opposite is true for countries such as Mexico or South Africa, where EV-ratios increased, thus becoming more detrimental.

Although Fig. 5 suggests differences amongst EV-ratios in 2019 for the various countries, there are also some general patterns that offer clues as to why these differences exist. Value added tends to be higher in countries where consumption takes place (in this study the EU) due to higher shares of value added toward the end of the value chain. Thus, EV-ratios tend to be lower within the EU than outside of the union. Further, when looking at the ranking of countries according to their GDP per capita (GDPpc) (Fig. 5, right ranking), there is a general pattern suggesting that wealthier countries tend to have lower EV-ratios than do poorer ones. Finally, as past research[22–25] suggests that countries positioned in the core of the trade network (that is, they are part of a cohesive subgroup of highly central, well-integrated trading countries) tend to experience comparably fewer environmental stresses, we also considered countries' Coreness score (see Supplementary Information for further details on calculating Coreness). The middle ranking found in Fig. 5 shows that several non-EU countries with relatively high Coreness scores (for example, China, RoW Asia and Pacific, RoW Middle East, RoW America and Mexico) also have high EV-ratios, suggesting there might be a positive, albeit weak relationship between Coreness and EV-ratios.

To explore these trends further, we ran multiple regression analyses on the 2019 data and then replicated these on the 1995 data to explore the extent to which patterns located in the former were also detectable in the latter. Our models input Coreness, GDPpc and EU membership (EU_mem) as explanatory variables predicting EV-ratios. These model results, along with the correlations between these four variables, can be found in Supplementary Tables 3 and 4.

The correlations in Supplementary Table 3 range from weak (GDPpc and Coreness) to moderately strong (Coreness and EU membership; GDPpc and EV-ratios). Bringing these variables into a regression model shows (for example, in model 1 for 2019) that EV-ratios are a function of the wealth, Coreness, and EU membership of countries, with all three holding negative, significant relationships with EV-ratios (Supplementary Table 4). Finally, we note that model 2, which replicates model 1 but for the data we have for 1995, shows many of the same patterns. The main difference is that GDPpc wealth seems to show a

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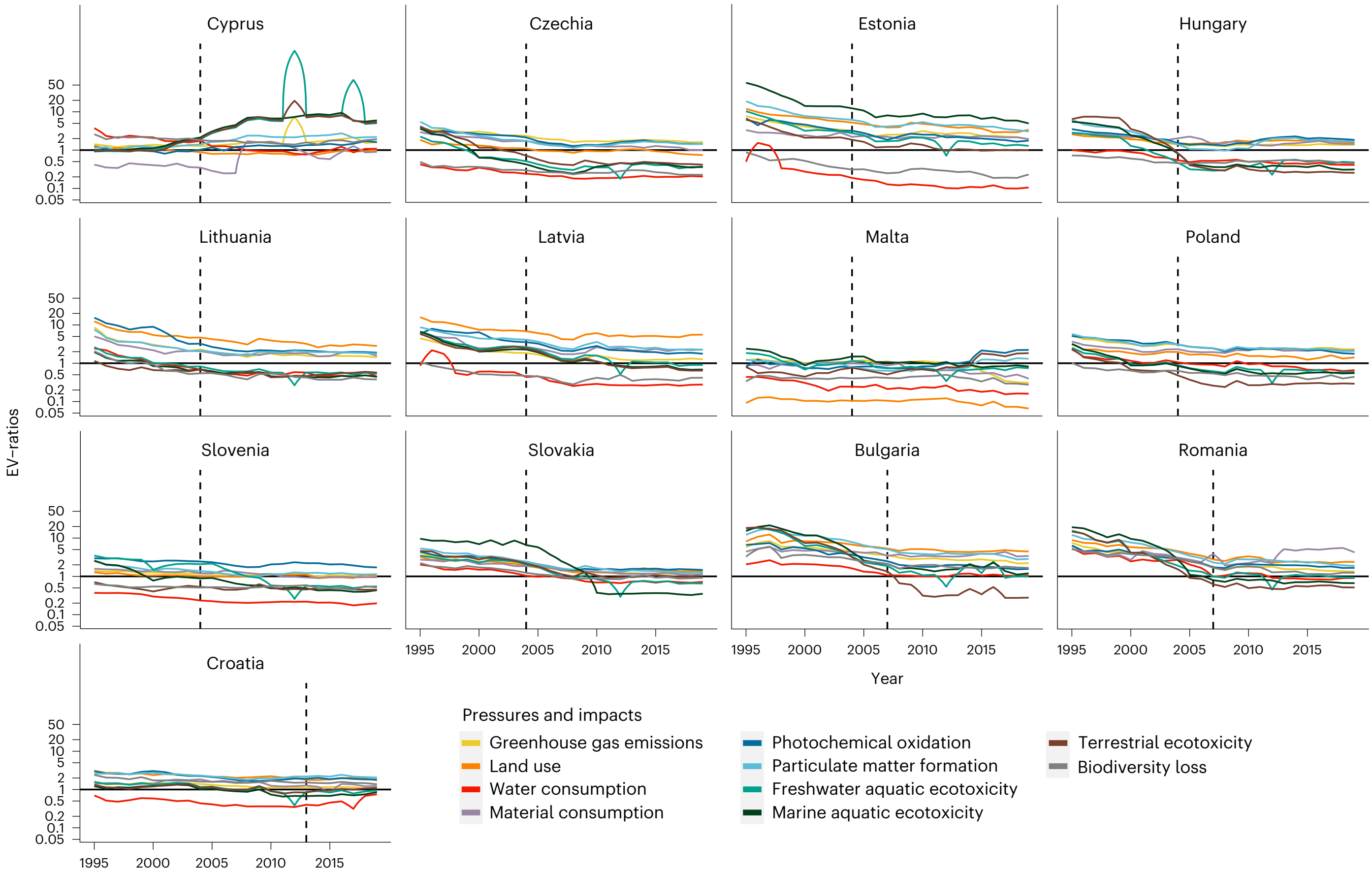

Fig. 6 | EV-ratios from 1995 to 2019 for pressures and impacts associated with EU-27 consumption for countries who joined the EU after 2000. Vertical black, dashed lines mark the year the country joined the EU.

weaker predictive pattern, especially when combined with EU membership, than what is shown in model 1. Taken together, these models support past research indicating wealth and network structure as important explanatory variables explaining between-country differences in EV-ratios[22–25].

EV-ratios decreased for new EU member countries

There are also notable differences amongst EU member countries. Countries which joined the EU before 1995, the starting year of this analysis, tend to have lower EV-ratios over the years than countries which joined the EU after 2000, especially Bulgaria, Estonia and Cyprus. The only exception is Greece, which joined the EU in 1995 but experienced the highest average EV-ratios of all member states in recent years, since they were >1 for all indicators except for land use and material consumption connected to EU consumption.

Despite on average still having higher EV-ratios in 2019 than long-term members, countries which joined the EU after 2000 experienced a significant decline in EV-ratios over the analysed period, except for Malta (no significant trend) and Cyprus (significant increasing trend), as seen in Fig. 6. For long-term EU members, EV-ratios increased in some countries, such as Germany, Ireland and Denmark, while they decreased slightly in others, such as Portugal, Finland, Spain or Sweden.

Discussion

The results of this research give a comprehensive account of environmental pressures and impacts from EU consumption over multiple decades. While there have been multiple studies on the global distribution of individual pressures and impacts from EU consumption[12,13] as well as studies determining total absolute pressures and impacts for member states[3–7] and at the subnational level[17,26], this research adds to the literature by assessing the global distribution of environmental pressures and impacts from EU consumption over time. Our results bolster previous findings on the distribution of blue water consumption[13], land use[8] and biodiversity loss from land use[12,27] induced by EU consumption. While previous studies highlight the large imports of indirect GHG emissions from China to the EU[28,29], our results suggest that EU consumption is also connected to high GHG emissions in Russia and countries in the RoW Asia and Pacific region. Moreover, the total increase of blue water consumption and material consumption and the decline for land use and GHG emissions connected to European consumption are well in line with the results of earlier studies[19,27,30,31].

We show that the EU's consumption was connected to displacement of large-scale environmental pressures and impacts outside of its borders. Seven of the analysed pressures and impacts (all ecotoxicity indicators, GHG emissions, particulate matter formation, photochemical oxidation and material consumption) increased notably outside the EU, while decreasing within. Outsourcing environmental pressures and impacts from richer to poorer regions is apparent on a global scale today[32], as pressures and impacts embodied in trade are growing[30]. Meanwhile, large-scale net flows of resources embodied in trade from poorer to richer countries, so called ecologically unequal exchange, have been confirmed in recent research[33,34]. The analysis of EV-ratios connected to EU consumption adds to the discussion on ecologically unequal exchange, as it highlights the unbeneficial situation for many non-EU countries.

The results indicate that EV-ratios associated with EU consumption are more beneficial for most member countries than for non-EU countries and regions. At the same time, EU consumption induced

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higher environmental pressures and impacts per value added in the RoW Europe region than anywhere else in the world. The region contains current EU candidate members, such as Albania, Montenegro or Serbia and new applicants, such as Ukraine and Moldova.

To avoid further detrimental effects on human health and ecosystems inside and outside the EU, it is paramount to decrease the environmental pressures and impacts associated with EU consumption. This can be achieved through multiple mechanisms. Consumption options, such as transportation mode and frequency or dietary choices can substantially reduce environmental pressures and impacts[35–37]. Since many super-affluent consumers, currently contributing disproportionally large shares to global environmental damage and resource use[2,6,7,12,38,39], live within the EU, mitigation efforts need to focus on affluence and overconsumption[40–42]. Moreover, new trade policies of the EU need to consider environmental pressures and impacts embodied in products and services, to prevent additional spill-over effects outside of the EU. Policies to reduce spill-over effects, such as for GHG emissions, need to consider inequalities in the process to provide a fair outcome for all[43].

Methodology

EEMRIO analysis

The input–output approach has been widely used for economic, environmental and societal analysis of economic structures[44]. Consumption-based environmental pressures and impacts along the supply chain of EU consumption can be calculated using the multiregional input–output (MRIO) framework, despite highly aggregated and imperfect datasets[45]. EEMRIO analysis has been applied in numerous studies to analyse environmental pressures and impacts of consumption and trade. A particularly common application is the computation of environmental footprints, such as ecological footprints and water footprints[46], GHG and biodiversity footprints[26] or carbon emissions and carbon footprints[17,47–49].

The EEMRIO approach uses an MRIO table, which consists of the inter-regional trade between m sectors in n countries. The data are collected in matrix $Z((mn)\times(mn))$, consisting of elements z_{ij}^{rs} as the inter-regional trade of sector i in region r into sector j in region s. Furthermore, it contains country-specific final demand vectors in matrix $F((mn)\times(tn))$ for t different categories.

The elements on the final demand matrix F are $f_i^{rs,\tau}$ for final demand in region s for sector i of country r in final demand category τ. First, the total output of each sector in each region is computed and stored in a column vector $\mathbf{x}((mn)\times 1)$, with elements x_j^s as the total output of sector j in region s. Subsequently, the $A((mn)\times(mn))$ matrix is calculated with equation (1). It consists of elements a_{ij}^{rs}, representing the technological production mix and efficiency.

$$a_{ij}^{rs} = \frac{z_{ij}^{rs}}{x_j^s} \tag{1}$$

The underlying formula of the MRIO framework can be simplified into:

$$(I-A)^{-1}f = x \tag{2}$$

Here, the Leontief inverse $(I-A)^{-1}$ consists of the identity matrix I and the A matrix. Moreover, an aggregated final demand vector $\mathbf{f}((mn)\times 1) = \left(f_i^r\right)$ is used:

$$f_i^r = \sum_{s=1}^{n}\sum_{\tau=1}^{t} f_i^{rs,\tau} \tag{3}$$

For multiple final demand vectors gathered in a final demand matrix F, equation (2) turns into equation (4).

$$(I-A)^{-1}F = X \tag{4}$$

Here, $X((mn)\times(tn))$ represents a matrix of total output vectors $\mathbf{x}^{s,\tau}$ induced by the final demand vectors $\mathbf{f}^{s,\tau}$ in F.

To account for environmental pressures and impacts the MRIO framework can be extended by premultiplying the total output x with environmental or socio-economic coefficients to determine pressures and impacts. These coefficients are stored in a column vector $\mathbf{c}((mn)\times 1)$ with elements $c_{j,k}^s$, which represent the pressure or impact k created by the production of one unit in sector s in region j.

Vector $\mathbf{c}$ is diagonalized into a matrix $\hat{c}((mn)\times(mn))$. By premultiplying the total output matrix X with the diagonalized matrix $\hat{c}$, a matrix of consumption-based pressures or impacts $E((mn)\times(tn))$ can be computed (equation (5)). The elements of matrix E, $e_{i,k}^{r,s,\tau}$ represent the consumption-based environmental pressure or impact k induced by final demand $f^{s,\tau}$ in sector r in region i.

$$E = \hat{c}X = \hat{c}(I-A)^{-1}F \tag{5}$$

Computation of environmental pressures and impacts

We selected one environmental impact, biodiversity loss from land use and nine environmental pressures: GHG emissions, blue water consumption, land use, material consumption, photochemical oxidation, freshwater aquatic ecotoxicity, terrestrial ecotoxicity, marine ecotoxicity and particulate matter formation, on the basis of the analysis of ref. [16]. Even though the selected indicators are able to explain most of the variance seen in environmental impact pathways available in EXIOBASE[16], they are not able to account for the full spectrum of human influence on the environment. We added indirect environmental impacts and pressures of EU consumption, which happen along the supply chain and direct impacts and pressures on the environment, such as carbon emissions from heating or driving fossil-fuelled cars. For seven out of ten indicators, indirect consumption-based pressures E are computed in a single step with coefficients in the diagonalized vector $\hat{c}$ in equation (5). Subsequently, the consumption-based results for sectors r and demand categories τ are summed up for each region i and direct pressures $\varepsilon_{i,k}$ are added (equation (6)) to compute the total pressure k induced in region i by final demand category τ in the EU, stored in matrix $\bar{E}$.

$$e_{i,k} = \sum_{r=1}^{m}\sum_{\tau=1}^{t} e_{i,k}^{r,\tau} + \varepsilon_{i,k} \tag{6}$$

However, consumption-based land use and material use associated with EU consumption are initially computed with coefficients for individual land and material use categories k. The different land occupations, such as cropland or pastureland or material categories, such as iron ore or forestry and timber, are subsequently summed up to quantify the total land and material use, as seen in equations (7) and (8).

$$\bar{E}_{\text{cropland}} + \bar{E}_{\text{pasture land}} + \ldots = \bar{E}_{\text{total land}} \tag{7}$$

$$\bar{E}_{\text{iron ore}} + \bar{E}_{\text{forestry}} + \ldots = \bar{E}_{\text{material use}} \tag{8}$$

Biodiversity loss due to land use requires an additional step, where land use results $e_{i,k}$ in individual categories k and regions i is multiplied with the respective biodiversity loss coefficients $\gamma_{i,k}$ for land use categories k in regions i. Equation (9) shows how biodiversity loss due to land use category k in region i is computed by element-wise multiplication of the land use results and the biodiversity loss coefficients. The equation is repeated for each final demand category τ in region s.

$$\epsilon_{i,k} = e_{i,k} \circ \gamma_{i,k} \quad (9)$$

Computation of value added

Value added linked to EU consumption is computed analogously to the environmental impacts and pressures using the EEMRIO approach and coefficients for value added along the supply chain. For these calculations, the elements $c^s_{j,k}$ in the diagonalized vector $\hat{c}$ in equation (5) correspond to the amount of value added generated by the production of one unit in sector s in region j.

Analysis of unequal impacts

We use the environmental pressures and impact calculated in the previous step to analyse the distribution of pressures and impacts associated with EU consumption in individual countries and regions. For analysing the impacts and pressures related to consumption of different products and services we use different final demand vectors $\mathbf{f}^{s,\tau}$. For all 27 member countries of the EU, which correspond to regions s in the EEMRIO-model we run the model with a set of seven different final demand categories τ, aggregated into total final demand and final demand of selected products and sectors aggregated into six previously used[38] consumption categories: food, shelter, clothing, services, manufactured products and mobility. Supplementary Table 2 shows the allocation of sectors to consumption categories.

Furthermore, we compare the distribution of environmental pressures and impacts associated with EU consumption with the distribution of associated value added across the world. First, we determine the country or regional shares of each pressure or impact induced by EU consumption. Subsequently, we compute the analogue shares for value added along the supply chain. Finally, we use the EV-ratio introduced by ref. [23] and used under different names in additional studies[22,24]. This indicator can be used to determine whether EU consumption is having a favourable or unfavourable effect in a country or region, by dividing the share of environmental pressure or impact experienced in the country by the share of value added. A value >1 indicates that a country or region is experiencing a higher share of pressure or impact than value added associated with EU consumption (unfavourable), while a value <1 shows that the country or region is experiencing a higher share of value added than environmental impact or pressure (favourable). In turn, a value of 1 would indicate that a country or region is experiencing the same share of pressures or impacts and value added associated with EU consumption.

Data

For the EEMRIO analysis we use the EXIOBASE v.3.8.1 database[14,50]. The database includes yearly input–output tables for 200 product sectors in 49 countries and regions, including all 27 EU member countries. We looked at a time span from 1995 (the first year available in EXIOBASE v.3.8.1) to 2019. Additionally, the database includes >1,000 individual socio-economic and environmental pressures and 126 impact categories. We use all seven final demand categories (final consumption expenditure by households, final consumption expenditure by non-profit organizations serving households, final consumption expenditure by government, gross fixed capital formation, changes in inventories, changes in valuables, exports: total free on board value) available in EXIOBASE for all 27 EU member countries to compute environmental pressures and impacts. The specific pressure and impact coefficients used for our analysis are summarized in Supplementary Table 1. To parse the raw EXIOBASE v.3.8.1 data we followed the methodology of ref. [51]. We chose EXIOBASE v.3.8.1 over other MRIOs, such as GTAP, due to its high amount of individual product sectors, the number of available pressure and impact coefficients and its full coverage of 27 EU member countries. The large-scale aggregation of countries into RoW regions, especially in Africa, Asia and South America but also in Eastern Europe is a clear limitation of using the EXIOBASE v.3.8.1 database to show where EU consumption causes pressures and impacts on the environment and where value added is generated. Thus, we can show which countries and regions are benefitting from EU consumption and which regions are experiencing disproportionally large environmental pressures and impacts. However, we cannot determine if there are specific groups of society, such as high-income segments, which are profiting highly from the value added associated with EU consumption, while others only benefit minimally. Additionally, some of the nine considered environmental pressures can have impacts that happen outside the country or region borders set by EXIOBASE. Hence, additional modelling steps following the impacts of environmental pressures, such as health impacts from atmospheric emissions after transportation[52] or impacts of water consumption in ecosystems downriver[53], would be needed for a comprehensive analysis of the impacts on human health and ecosystems associated with EU consumption.

The indicator used to quantify GHG emissions along the supply chain is an aggregated indicator from the EXIOBASE database v.3.8.1, accounting for multiple GHGs (CO_2, CH_4, N_2O, SF6, HFC and PFC) in kgCO_2e on the basis of their global warming potential over 100 yr, as suggested by the IPCC report[54]. It is noted that GHG emissions of EXIOBASE dataset include emissions from combustion, non-combustion, agriculture and waste but exclude emission from land use, land use change and forestry[55]. To compute associated material use of EU consumption, coefficients for material use in multiple categories (domestic extraction used of crop and crop residue, grazing and fodder, forestry and timber and so on) were aggregated to an indicator for total material use (in kt). Land use was initially calculated for 20 different land occupation categories (cropland, forest area, infrastructure land and other land use) and subsequently summed to determine the total land use linked to EU consumption (in km^2). The water consumption induced by EU consumption was computed using aggregated coefficients for total blue water consumption in different parts of the economy, such as agriculture, manufacturing or electricity. Freshwater aquatic, marine aquatic and terrestrial ecotoxicity are quantified using aggregated indicators from EXIOBASE via a problem-oriented approach[56,57], which weighs the impacts of freshwater aquatic ecotoxicity potential, marine aquatic ecotoxicity potential and terrestrial ecotoxicity potential for each emission of a toxic substance to air, water and/or soil and measures them in kilograms of 1,4-dichlorbenzene equivalents. The infinite impacts are chosen on the basis of the recommendations of the International Reference Life Cycle Data System[58]. To account for photochemical oxidation associated with EU consumption, caused by the emission of substances such as non-methane volatile organic chemicals or carbon monoxide we use an aggregated and weighted indicator measuring the kilogram of formed ozone. As suggested by ref. [16], we chose the indicator using the maximum incremental reactivities method. Finally, particulate matter emissions are determined using emission-weighted coefficients in kilogram $PM_{2.5}$ equivalents. Value added associated with EU consumption along the supply chain is determined using coefficients for value added in € million from EXIOBASE v.3.8.1. More details for the selected indicator are shown in Supplementary Table 1.

Additionally, we used land occupation specific biodiversity loss coefficients from ref. [12] specifically developed for the 49 EXIOBASE regions, accounting for biodiversity loss by measuring the potential disappearing fraction of species (PDF). The coefficients were computed using the LC-IMPACT life cycle impact assessment model[59], which provides land occupation specific PDF coefficients for 804 different ecoregions and is in turn based on previous studies[60,61]. We chose PDF in this study to quantify the global impacts of land used associated with EU consumption, as it is able to determine possible global extinction and takes into account species specific habitat characteristics and threats. Nevertheless, this metric does not account for changes in local relative species abundancy, which can be quantified using additional, complementary metrics[62]. For the multiple regression analysis, average

GDPpc values in purchase-power-parity 2017 US$ for all 49 EXIOBASE regions were computed using the World Development Indicators DataBank[63]. If no data were available for a country, data were added from the World Economic Outlook (October 2022)[25]. Population data to calculate averages for the aggregated RoW regions were taken from the United Nations World Population Prospects 2022[64]. Shapefiles for creating maps were retrieved from Natural Earth[65] and the eurostat R package[66].

Limitation

There are several limitations of this study. First, results of some pressures and impacts (for example, water consumption) since 2011 are based on a now-casting routine that projects relationships between the environmental usage and economic activity forwards. To validate the now-casted pressures and impacts, we had a look at the coefficients in EXIOBASE v.3.8.1, as economic data are up to date until 2019. The coefficients for country-sector pairs of the environmental indicators used in this study do not change notably over the years with non-now-casted data (before 2011), reflecting incremental changes in efficiency over the years. Similar trends are projected in the now-casting routine for the following years, up until 2019. Moreover, it would require enormous amounts of additional effort to update the indicator system for all indicators and countries, several thousand coefficients. Updating those global databases is indeed a general problem. Considering that the economic data are in fact up-to-date and that the environmental coefficients are not changing substantially over time, we think it is reasonable to use the now-casted values provided by EXIOBASE.

Second, the indicators are chosen on the basis of the analysis of ref. [16], which was done for base year 2011 only, rather than covering the whole time frame of this study. We do not expect large changes compared to the base year used in the analysis, as ref. [16] analyse the variance of environmental indicators amongst each other, which are not expected to change substantially over time. The dynamics that we show are mainly due to structural changes in trade, economic structure and consumption patterns more so that changes in environmental coefficients over time.

Third, according to EXIOBASE, the data are obtained via a problem-oriented approach[56,57]. The ecotoxicity indicators used in the paper reflect freshwater aquatic ecotoxicity potential for each unit of emission of a toxic substance to air, water and/or soil (in kg 1,4- dichlorobenzene equivalents per kg emission), marine aquatic ecotoxicity potential for unit of each emission of a toxic substance to air, water and/or soil (in kg 1,4-dichlorobenzene equivalents per kg emission) and terrestrial ecotoxicity potential for each unit of emission of a toxic substance to air, water and/or soil (in kg 1,4- dichlorobenzene equivalents per kg emission). Although in a comparison ecotoxicity results from EXIOBASE can be significantly smaller than life cycle assessment results[67], for consistency, we use EXIOBASE indicators in the whole study.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Final demand data for the 27 EU member countries, as well as global MRIO tables and environmental extensions were retrieved from the EXIOBASE v.3.8.1 database (https://zenodo.org/record/4588235)[14]. Coefficients for biodiversity loss from land use were collected from ref. [12]. Data for calculating regional average GDPpc were retrieved from the World Development Indicators DataBank (https://databank.worldbank.org/source/world-development-indicators)[63], the World Economic Outlook (October 2022) (https://www.imf.org/external/datamapper/datasets/WEO)[25] and the United Nations World Population Prospects 2022 (https://population.un.org/wpp/)[64]. For creating maps, shapefiles from Natural Earth (https://www.naturalearthdata.com/)[65] and the Eurostat R package[66] were used. Data for recreating the results and figures are available in the Supplementary Code. The main results are collected in the Supplementary Data.

Code availability

Code developed for data processing in MATLAB, Python and R are available in the Supplementary Code.

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Author contributions

K.H., Y.S. and B.B. conceptualized and designed the study with crucial inputs from K.F. and H.Z. B.B. performed the MRIO and EV-ratios analysis with help from Y.S. and Y.Z. C.P. performed the social network and regression analysis with help from Y.Z. Y.S., C.P. and B.B. prepared the manuscript. B.B., K.H., C.P. and Y.S. contributed to writing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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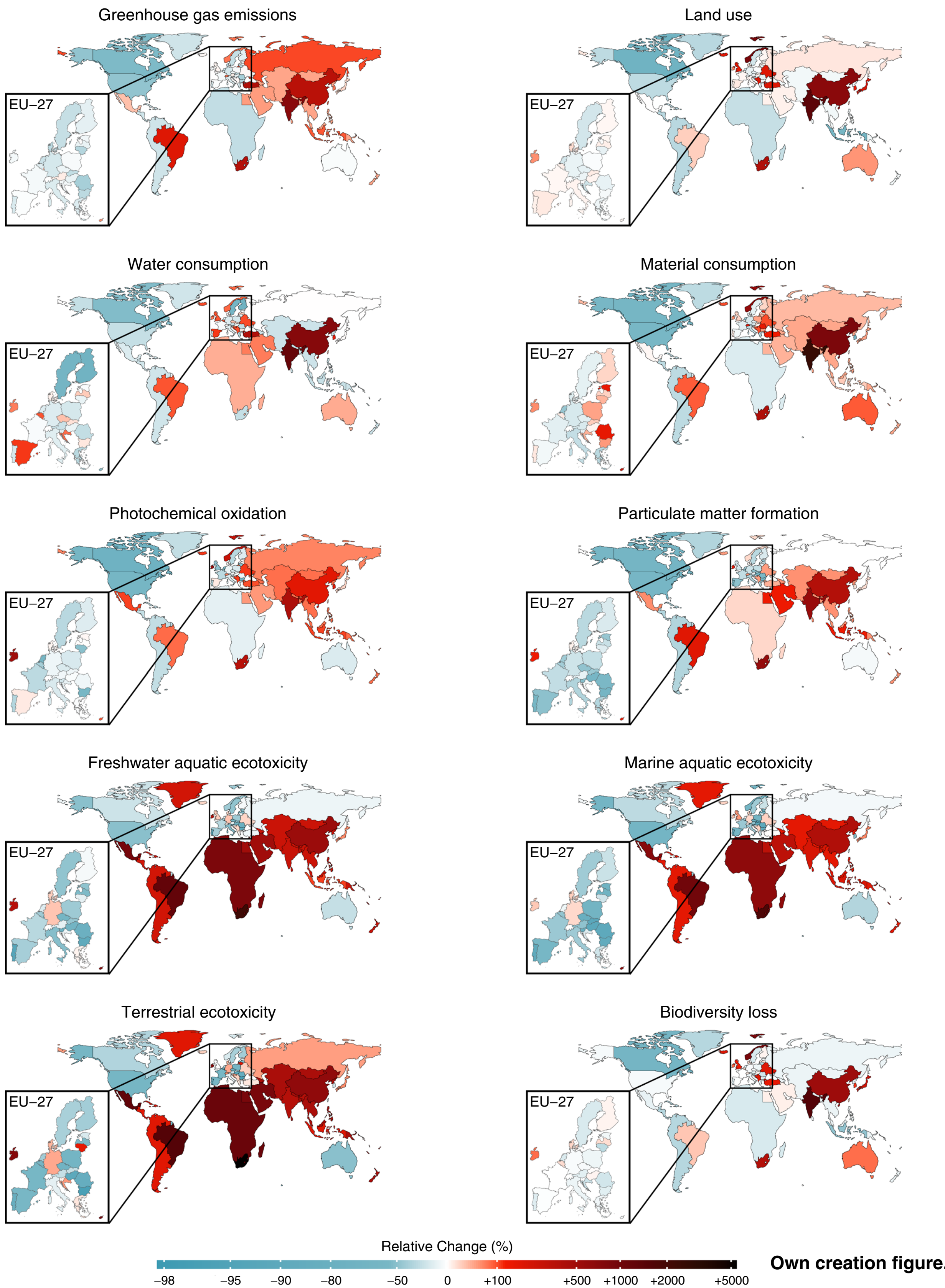

Extended Data Fig. 1 | Relative change of pressures and impacts associated with EU-27 consumption between 1995 and 2019. Relative changes within EU-27 countries are highlighted in an extra panel in the bottom left. The ecotoxicity results from EXIOBASE dataset have to be seen as lower bounds.

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Code for parsing the raw EXIOBASE 3.8.1 data was partly retrieved from Hardadi et al. (2020) and https://github.com/ghardadi/correspondencematrix.
Data analysis	n/a

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

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Final demand data for the 27 EU member countries, as well as global MRIO tables and environmental extensions were retrieved from the EXIOBASE 3.8.1 database (ref. 14, https://zenodo.org/record/4588235). Coefficients for biodiversity loss from land use were collected from (ref. 12). Data for calculating regional average GDP per capita was retrieved from the World Development Indicators DataBank (ref. 59, https://databank.worldbank.org/source/world-development-indicators), the World Economic Outlook (October 2022) (ref. 60, https://www.imf.org/external/datamapper/datasets/WEO) and the United Nations World Population Prospects 2022 (ref. 61, https://population.un.org/wpp/). For creating maps, shapefiles from Natural Earth (ref. 62, https://www.naturalearthdata.com/) and the eurostat R package (ref. 63) were used. Data for recreating the results and figures are available in the Supplementary Information. The main results are collected in Supplementary Table 1.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	n/a
Population characteristics	n/a
Recruitment	n/a
Ethics oversight	n/a

Note that full information on the approval of the study protocol must also be provided in the manuscript.

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	In this study we analyse the global distribution of ten environmental pressures and impacts, as well as value added associated with EU consumption from 1995 to 2019 using an environmentally-extended multi-regional input-output (EEMRIO) approach. We determine how these environmental pressures and impacts are distributed over 44 countries and five rest of the world regions, using the EXIOBASE 3.8.1 database, and how they have changed over the analysed period. Additionally, we compute the national emissions-to-value-added-ratio (EV-ratio) for each of the ten indicators to compare the distribution of environmental pressures and impacts with the distribution of value added induced by EU consumption. We compute coreness and GDP per capita values for each EXIOBASE 3.8.1 region in 1995 and 2019 and perform a multiple regression analysis to determine the driving factors of national average EV-ratios.
Research sample	The study looks at ten environmental pressures and impacts and value added associated with EU consumption from 1995 to 2019 in 44 countries and 5 rest-of-the-world regions, based on the EXIOBASE 3.8.1 database.
Sampling strategy	We selected the ten environmental indicators based on the analysis by Steinmann et al. (2018). We chose EXIOBASE 3.8.1 for the EEMRIO analysis due to its detailed coverage of EU member countries and environmental indicators, as well as providing yearly input-output tables as well as environmental coefficients. 1995 was chosen as the starting year for the analysis, as the earliest year available in EXIOBASE 3.8.1 and 2019 was chosen as the final year with reliable economic data before the COVID-19 pandemic. Coreness values and GDP per capita values were computed for 1995 and 2019 to determine their influence an average EV-ratios over the analysed period.
Data collection	Data for the EEMRIO analysis, including input-ouput tables, final demand and environmental pressure coefficients were downloaded from the EXIOBASE 3.8.1 database (https://zenodo.org/record/4588235). Biodivesrity loss coefficients for land use were retrieved from Koslowski et al. (2020). Data for calculating regional average GDP per capita was collecetd from the World Development Indicators DataBank (https://databank.worldbank.org/source/world-development-indicators), the World Economic Outlook (October 2022) (https://www.imf.org/external/datamapper/datasets/WEO) and the United Nations World Population Prospects 2022 (https://population.un.org/wpp/). We retrieved shapefiles from the Natural Earth repository (https://www.naturalearthdata.com/) for creating world maps and we used the eurostat R package (ref. 63) for creating maps of the EU member states.
Timing and spatial scale	This study uses data from the EXIOBASE 3.8.1 dataset for 44 countries and 5 rest-of-the-world regions from 1995 to 2019.
Data exclusions	The analysis is based on the EXIOBASE 3.8.1 database, which does not provide individual data for all countries, but groups some countries into rest-of-the-world regions.
Reproducibility	Results can be reproduced using the EXIOBASE 3.8.1 database and the code and data provided in the Supporting Information.
Randomization	n/a
Blinding	n/a

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging