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Letter to the Editor

Correlation between production and consumption-based environmental indicators
The link to affluence and the effect on ranking environmental performance of countries

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ABSTRACT

Countries and international organizations such as the European Union and the OECD work with dashboards of sustainability indicators, which include sets of pressure indicators that reflect the performance of a country. Such indicators can be calculated for production – reflecting the volume and efficiency of a national economy, but also its specialization – and with respect to consumption, which more closely reflects impacts of lifestyles and includes the effects embodied in international trade. We determined production- and consumption-based pressure indicators for greenhouse gas emissions, material, water, land use, and solid waste using the EXIOBASE global multi-regional input-output model. We investigated the correlation among different production- and consumption-based indicators with each other, with the well-known ecological footprint, and with purchasing power parity-adjusted gross domestic product (GDP_{PPP}), all expressed per capita. Production-based indicators and GDP_{PPP} were moderately correlated, with the highest correlations between the pairs [carbon, GDP_{PPP}] and [land, water] ($\rho = 0.7$) and low or no correlation between other pairs. For the footprint indicators, however, we find a strong coupling between the carbon, water, materials and ecological footprints, both to each other and to GDP_{PPP} ($\rho = 0.8$–0.9 for all combinations). In general, the consumption-based approach shows a much stronger coupling of environmental pressures to affluence than the production-based environmental indicators. The high correlations among footprints and with affluence make it difficult to conceptualize how we will decouple environmental impact from affluence at a global level. Further research is required to investigate the impact of economic specialization, and to discover new options for decoupling environmental footprints from GDP per capita.

1. Introduction

Sustainable development policies must take into account the complexity of socio-ecological systems, particularly to avoid problem shifting across regions (Helm, 2012; Peters, 2008) or environmental issues (Hertwich et al., 2014; Jin et al., 2015; Verdade et al., 2015). To illustrate the complexity of human-environment interactions, comprehensive sets of indicators to assess the impacts of production and consumption have been developed. Indicator spectra, including the Green Growth Indicator Set (OECD, 2014), the European Commission's environmental pressure indicators framework (European Commission, 2003, 2001) and the European Union's Resource Efficiency Scoreboard (European Commission, 2016) are used to assess the environmental performance of countries. Measures such as the Environmental Performance Index (Hsu et al., 2014), the Environmental Impact Index (Bradshaw et al., 2010) and the Ecological Footprint (Borucke et al., 2013) aggregate environmental pressures for multiple issues occurring within a country or region.

Indicators that account for environmental impacts within a country (following the production-based accounting principle) don't necessarily show convergence across indicator sets, often due to a country's technological specialization and resources availability (European Commission, 2003), and are thus complementary to include in indicator sets. To internalize differences not only in technology efficiency but also in production specialization, and to capture differences in resource use due to shift of industries to resource-abundant countries, some have argued that consumption-based indicators are required to capture the real sustainability of lifestyles (Peters, 2008; Peters and Hertwich, 2008; Tukker et al., 2016; Wiedmann, 2009; Wiedmann and Barrett, 2013). Consumption-based indicators, also called footprints, link the consumption of products and services with environmental impacts by accounting for pressures occurring along the global supply chains of these products. These footprints are now widely used to measure the appropriation of natural capital and resources or the generation of emissions associated with human activities.

To comprehensively capture the different aspects of sustainable lifestyles, some authors combine different footprints into a dashboard of pressure indicators, such as the footprint family (Galli et al., 2013, 2012) comprising of carbon, water, and ecological footprints; and the multi-indicator analysis to study Europe's footprints and resource deficit for carbon, land, water (in particular blue water consumption) and material (Tukker et al., 2016). Other dash-

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boards combine production- and consumption-based indicators to assess environmental impacts, such as the one used by the European Commission in its "Roadmap to a Resource Efficient Europe" (European Commission, 2011). Since the proposed dashboards of footprints were defined *a priori*, one needs to examine their actual usefulness. Do the footprint dashboards really convey a different narrative compared to single indicators? This study tries to establish the correlation between different environmental footprints with one another and with economic affluence, at the same time that it compares the national footprints with a similar dashboard of production-based pressures. We include policy-relevant indicators that have been frequent in the analysis of countries' environmental performance: ecological, carbon, water, material, land and waste.

A high correlation between environmental performance indicators of societies has two immediate consequences. First, high correlation suggests that the different environmental footprints are strongly coupled to some underlying mechanisms in the countries' socioeconomic metabolism. Decoupling one indicator from affluence or wellbeing may depend on the simultaneous decoupling of others, which means that sustainable development may represent a much larger challenge that anticipated. Second, the information content of the dashboard might be lower than the variety of indicators suggests. This may have consequences for the usefulness of such dashboards. Previous studies have shown that various environmental footprints are, at least partially, correlated with affluence (Hertwich and Peters, 2009; Wang et al., 2016; Weinzettel et al., 2013; Wiedmann et al., 2013). Other studies have shown that about half of the environmental impact indicators in the life cycle assessment of products are highly correlated to fossil energy demand (Huijbregts et al., 2010, 2006) and that product footprints for different environmental accounts are often highly correlated among each other (Pascual-González et al., 2015). These different studies suggest a potential correlation among environmental pressure caused by the production or consumption of goods and their relationship to affluence, commonly measured by GDP or consumption levels, but the degree of correlation across the board of indicators is not available in the current literature. This study tries to fill this gap.

2. Methods

We calculated the correlation of the most commonly used production- and consumption-based pressure indicators – carbon, blue water, material, land, solid waste – with one another, with the well-known ecological footprint (Borucke et al., 2013) and with affluence, measured in purchasing power parity-adjusted gross domestic product (GDP_{PPP}) per capita. We illustrated the consequences of such correlation on the ranking of countries according to their environmental pressure per capita. In addition, we investigated how an aggregated indicator based on several footprints would perform depending on how the different footprints are combined.

2.1. Calculation of environmental pressure indicators

The environmental indicators used in this analysis are listed in Table 1. The calculation of environmental footprints and production-based pressures (with exception of ecological footprint) were performed using the high-resolution environmentally-extended multi-regional input-output (EE-MRIO) EXIOBASE database (Wood et al., 2015). This input-output model details the flows of goods and services throughout the global economy, and is coupled with a variety of resource use and environmental pressures in the same classification. In its version 2.3, used in this study, EXIOBASE describes the world economic system for the year 2007 in a detailed product resolution. It comprises 43 countries, which together account for around 90% of global GDP, and five "rest-of-the-world" regions. The countries are the 27 European Union[1] countries and 15 other major world economies including the US, China, India, Russia, and Brazil. The full lists of regions in EXIOBASE are available in the supplementary information (SI). For this study we used 42 countries.[2]

Production-based pressures were calculated by summing all impacts and resource use within domestic industries and direct impacts in final demand (households, governments, and fixed capital formation). The calculation of environmental footprints was done by allocating impacts and resource use occurring domestically and in foreign regions throughout the global supply chain to the final consumption of the goods and services in the assessed country, summed with direct impacts in final demand, through an EE-MRIO analysis (Peters and Hertwich, 2004). A more detailed description of the EE-MRIO method and the data sources for environmental extensions from EXIOBASE are available in section S1 of the SI.

Production-based impacts were considered for every indicator, except for the ecological footprint, in order to maintain methodology consistency as production accounts for ecological footprints are not available from the Global Footprint Network. Population and GDP_{PPP} data for the year 2007 were retrieved from The World Bank (2016).

2.2. Correlation and construction of an aggregated indicator

We calculated Pearson product-moment correlation coefficients (ρ) for each production- and consumption-based indicator with each other and with per capita GDP_{PPP}. To illustrate the implication of these correlations, we compared the ranking of countries for each of the indicators and we aggregated the different environmental footprints into a single score. We present the aggregation of the three highest correlated footprints – carbon (C), material (M), and water (W) – into an aggregated index (I). To explore the effect of weighting on the potential compound index we performed a Monte Carlo analysis by screening 10 000 different arbitrary random weighting schemes applied to the normalized carbon, material and water footprints according to Eq. (1).

$$I(C,M,W) = \alpha\left[\frac{C - C_{\min}}{C_{\max} - C_{\min}}\right] + \beta\left[\frac{M - M_{\min}}{M_{\max} - M_{\min}}\right] + \gamma\left[\frac{W - W_{\min}}{W_{\max} - W_{\min}}\right], \qquad (1)$$

$$\alpha + \beta + \gamma = 100$$

3. Results and discussion

The 42 countries assessed represented the majority of impacts worldwide in 2007. For production-based impacts, these countries were responsible for 81% of global GHG emissions, 75% of domestic extraction used, 67% of blue water consumption, and 59% of global land use. When accounting for global supply chains, the share of these countries footprints in the global resource use becomes even higher: 87% for carbon, 86% for material, 80% for water, and 80% for land footprints.

Fig. 1 shows the correlation between environmental pressures indicators with one another and with GDP_{PPP} in the 42 countries assessed. On the left, it shows the correlation between production-based indicators, and on the right, the consumption-based footprints. With the notable exception of greenhouse gas

[1] EXIOBASE is currently being updated to a new version (Stadler et al., Submitted), with the inclusion of Croatia in the EU. In all versions of EXIOBASE the United Kingdom is included as an EU member.

[2] We excluded Taiwan from the analysis due to the lack of ecological footprint accounts and all rest-of-the-world regions due to the high regional aggregation.

Table 1
Environmental indicators used in this study and its coverage, units, and source of data.

Indicator	Coverage	Unit (per capita)	Source
Carbon	Greenhouse gas emissions Comprises CO_2, CH_4, N_2O, and SF_6	t CO_2e	EXIOBASE
Material	Material input to the economy Comprises primary crops, crop residues, fodder crops, grazing, wood, aquatic animals, metal ores, non-metallic minerals, and fossil fuels	tons	EXIOBASE
Water	Blue water consumption Comprises water consumed in agriculture, livestock, manufacturing, electricity, and households	m^3	EXIOBASE
Land	Total land use Comprises arable land, pastures, and forests	1000 m^2	EXIOBASE
Waste	Solid waste and scrap Solid waste comprises wood, ash, food, paper, plastic, inert or metal waste, textiles, and oil and hazardous substances for landfilling, bio-gasification, or incineration. Scrap comprises scrap metal, as well as other materials for recycling, such as construction materials, ash, glass, paper, wood, and plastics	tons	EXIOBASE
Ecological[a]	Demand on bioproductive area Comprises cropland, grazing land, fishing grounds, forest area for wood products, built-up land, and forest area to absorb CO_2 emissions	Global hectares (gha)	Borucke et al. (2013)

[a] No production-based pressure was considered for the ecological footprint.

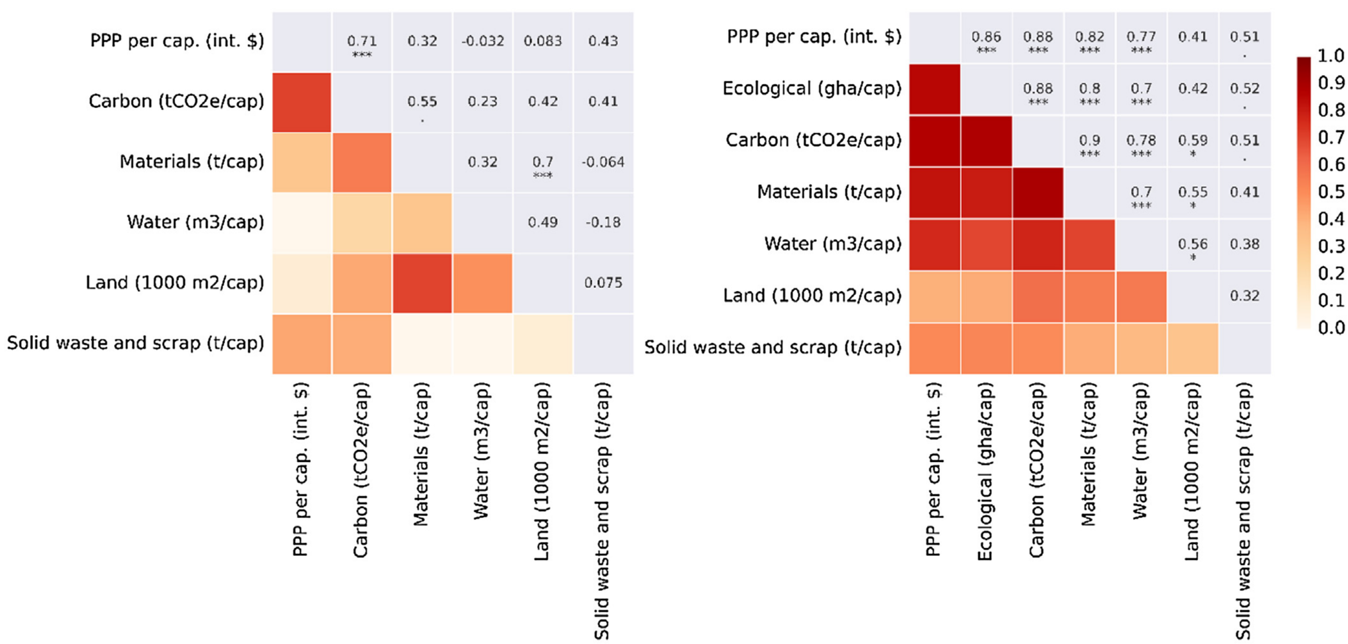

Fig. 1. Correlations (Pearson product-moment correlation coefficient) among production-based environmental pressures per capita (left) and environmental footprints per capita (right) across the 42 EXIOBASE countries and the gross domestic product per capita in purchasing power parity (GDP_{PPP} per capita) in 2007. The correlation coefficients are shown both as numbers and on a color scale. Darker shades represent stronger linear correlation. Correlation coefficients may vary between −1 and 1, where 1(−1) indicates perfect linear (anti-linear) correlation between two variables, and 0 indicates no linear correlation at all. Significant correlations are indicated by * ($P \leq 0.05$), ** ($P \leq 0.01$) and *** ($P \leq 0.001$).

emissions, pressures within country borders caused by domestic production processes are mostly not or only weakly correlated with GDP_{PPP} (Fig. 1 left). Domestic material consumption is correlated with land use and more weakly with GHG emissions, while other correlations are not significant. The lack of stronger correlations on production-based environmental pressures occurs possibly due to specific national characteristics, such as differences in natural conditions and resource endowments, economic specialization, subsidies and national industrial policies, or due to countries having taken different decisions about avoiding or mitigating such pressures (Duchin and López-Morales, 2012; Fracasso et al., 2016). Thus, different environmental accounts should be considered simultaneously to obtain a complete picture of environmental pressures occurring within the territory of a country.

Consumption-based accounts, meanwhile, show much stronger correlation to each other and to GDP_{PPP} (Fig. 1 right). Especially ecological, carbon, materials, and water footprints show high correlation among themselves and to GDP_{PPP}. The correlation of waste footprint with other indicators is weak and so is the correlation of the land footprint with the ecological footprint and the GDP_{PPP}. The correlation between production- with consumption-based indicators can be found in Fig. S1, in the SI.

Comparing the two panels in Fig. 1, we find that considering the effect of trade either introduces or significantly strengthens the correlations among the different pressure indicators. Such an increased correlation is in itself not surprising, as we subtract things that are unique for countries and add from a common pool. We would argue, however, that the strength of the effect is still noticeable. A growing body of literature has studied the role of

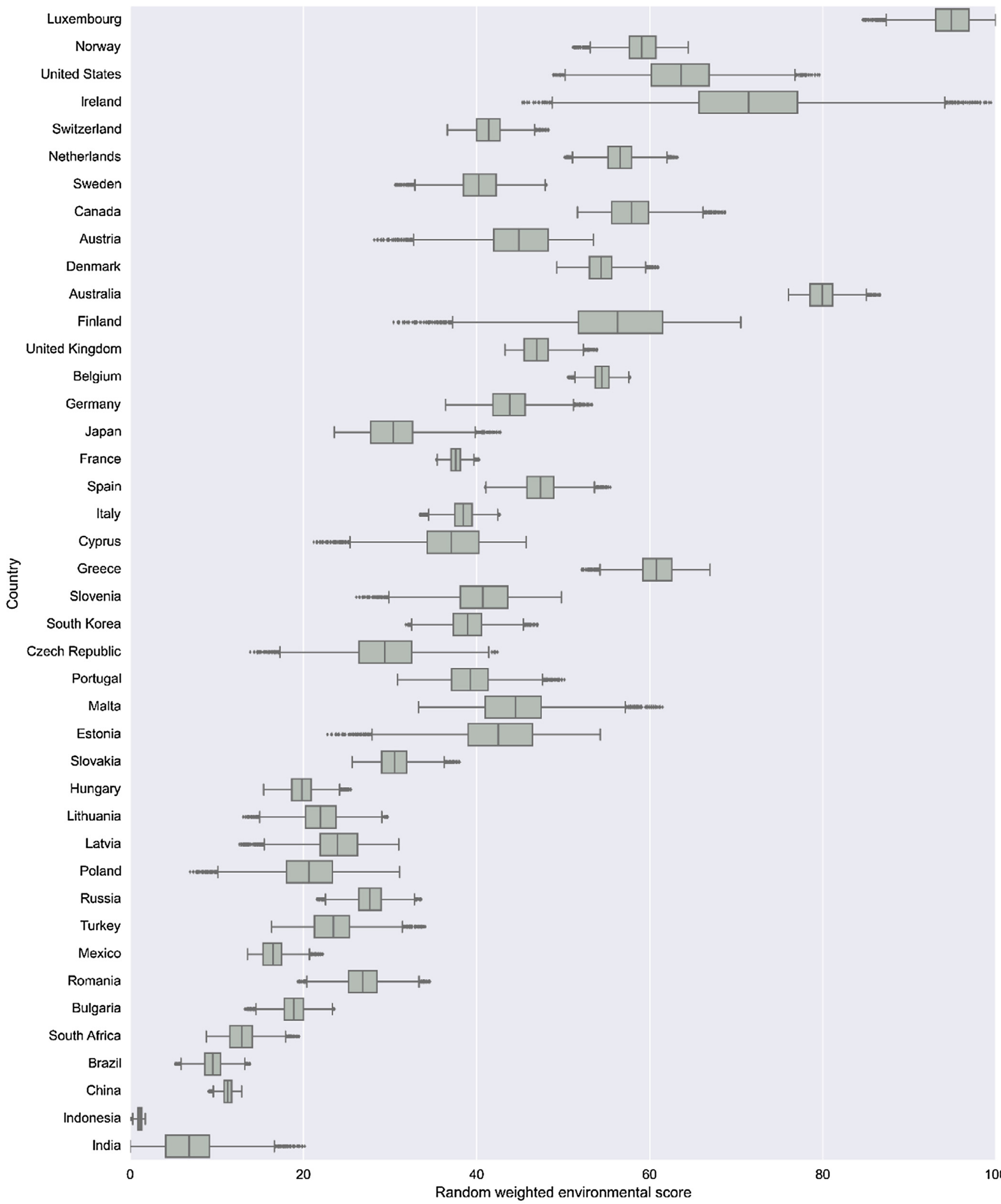

Fig. 2. Environmental scores obtained from arbitrary random weighting of the carbon, water and material footprints for the 42 EXIOBASE countries, 10 000 simulation runs. Countries ordered by GDP_{PPP} per capita. The middle line of each box shows the median, the box spans the inter-quartile range (25–75% of data points) with the whiskers spanning 1.5 time this inter-quartile range. Points outside this range are indicated by discrete points.

industry outsourcing in the reduction of production-based environmental impacts and the growth of "virtual" flows of impacts through trade (Dittrich et al., 2012; Hertwich et al., 2010; Peters and Hertwich, 2008; Tukker et al., 2016, 2014; Wiedmann et al., 2013). Other factors may be needed to explain this pattern. The increasing specialization of countries in their production may contribute to differences in environmental pressures, while increasingly similar lifestyles comprising the consumption of some of the same consumer products may contribute to the high correlation of footprint indicators. If similar products with similar footprint intensities are consumed, higher expenditure will drive higher impacts.

Previous studies have found high correlations between the carbon (Hertwich and Peters, 2009), land (Weinzettel et al., 2013), and material (Schandl et al., 2016; Wiedmann et al., 2013) footprints with GDP. A high correlation of materials and water footprints was also expected, as an important part of materials footprints is related to biomass, and between materials and carbon footprints, as carbon-intensive construction materials such as steel, cement and fossil fuels constitute most of the growth in material footprints in the past decades (Allwood et al., 2010; Dittrich et al., 2012). A significant correlation of ecological footprint with the land and carbon footprints was expected, as the ecological footprint contains components of land use and land theoretically required to absorb emitted carbon (Borucke et al., 2013; Giampietro and Saltelli, 2014). We find a significant correlation with carbon but not land footprints. In addition, we find a low correlation between the land footprint and GDP_{PPP}. These low correlations may be due to differences in the calculation of the land footprint. For the ecological footprint, Borucke et al. (2013) normalized land use with crop- and country-specific yield factors to obtain a global equivalent land use that is a reflection of the biomass production potential consumed rather than the actual land use. Weinzettel et al. (2013) also used this equivalent land use and in addition controlled for the per-capita availability of fertile land. In this study, however, we use total land use, without distinction of productivity or land availability. The solid waste and scrap footprint, which measures the total solid waste and scrap generated in a country's global supply chain, is only weakly correlated with the GDP_{PPP}-carbon-materials cluster, which may be a result of very different waste intensities across industrial sectors and countries, but large data gaps remain for this account (Merciai et al., 2013).

One application of per-capita environmental pressure indicators and footprints has been for producing country rankings, which are supposed to reflect the performance of a country in comparison with others. We explore the effect of the observed correlations on the rankings, by (1) comparing rankings produced with different indicators in Table 2, and by (2) evaluating an arbitrary weighting of a carbon-water-material footprints index in Fig. 2.

Country rankings based on different production-based environmental pressure indicators are not very consistent across the different environmental issues investigated (Table 2 left). The ranking pattern changes, however, when switching to consumption-based accounting (Table 2 right). The country rankings based on different footprints per capita are more similar, reflecting the correlation among underlying footprints. Internalizing trade in the country rankings show that, although technology changes are vital for a country's production-based impacts, higher consumption per capita of goods produced elsewhere have a substantial impact on decreasing the environmental performance of affluent countries. As reflected by the high correlations between footprints and GDP_{PPP}, similar trends of increasing environmental pressures with personal purchasing power can be observed across mainly carbon, material, and water accounts compared to the production-based rankings.

There are a number of outliers, however, that should be addressed individually. For example, the high land and waste footprints for Russia, which scores low on the other indices, and the high water footprints of Malta and Greece. Curiously, two countries with a very high per capita GDP_{PPP} present relatively low footprints for material (Switzerland) and ecological (Norway). These outliers might be influenced either by different consumption patterns, unique technologies or policies in local production, and to some extent data quality and availability. These cases show that, while there is much more consistency in the environmental performance of countries when looking through a consumption-based approach, there might be important differences in the resource appropriation of different countries. A thorough study of these differences and how they have changed in recent years might contribute to understanding how to improve decoupling of environmental footprints from GDP per capita.

The environmental production-based pressures and footprints per capita for each country are available in Table S2 the supplementary information. One could cluster countries with similar characteristics and perceive the similarities in their environmental pressures. For example, countries with highest land area and highest availability for fertile land per capita (Australia, Canada, Russia) have high pressure on land when accounted for both production-based pressures and footprints. Countries with the lowest land availability per capita (Malta, South Korea, Switzerland, Netherlands, Belgium) have high ratios between land footprints and production-based pressures, showing their dependency on imported embodied land. Higher differences between production-based pressures and footprints are seem for land and water accounts.

The high correlation between the carbon, material and water footprints raises the question whether the information contained in these indicators could be conveyed in one single aggregate measure. Deriving an index based on the aggregation of multiple indices includes a normative aspect: how much weight should be given to each individual indicators before the aggregation. However, since the indicators considered here are highly correlated (material, carbon and water footprint, see Fig. 1), different weighting schemes should only have a limited effect on the country ranking and reveal the same trend of higher environmental stressor with increasing affluence as observed for the individual indicators. To test this hypothesis, we performed a Monte Carlo analysis with 10 000 randomly chosen weighting schemes.

This leads to compound indices that cover rather narrow ranges for many countries, including the Netherlands, France, or Brazil (Fig. 2), but a much higher spread for other countries, including Ireland, Finland, and India. The latter three countries are characterized by one single deviating footprint which lie outside the range expected based on the other indicators for this country. Ireland, for example, has a particular high material footprint (see Tables 2 and S2); the weighting scheme focusing on the material requirements lead to amplify the scores, which put Ireland at the top of all countries. Finland, on the other hand, has a particular low water footprint. Therefore, the weighting schemes which put a focus on the water footprint result in a low overall score for Finland. For India, the water footprint is much higher than it would be expected based on affluence or the other footprint values. Nevertheless, the overall trend of increasing footprints with increasing level of affluence appears to be robust and, in most cases, insensitive to the applied weighting schemes. For footprints with lower correlations, the ranges increase considerably. For all production-based pressures, no trend can be identified (see also Figs. S2 and S3).

4. Conclusion

Due to different socioeconomic and technological characteristics, production-based environmental impacts vary significantly across countries. Each of the indicators for the various environmental pressures indeed provides distinct information. In contrast to production, consumption-based footprints offer more uniform patterns of environmental impact on the national level. The relative performance of a country with respect to one environmental footprint provides a good indication as to how this country will per-

Table 2
Ranking of the 42 EXIOBASE countries according to their footprints and production-based accounts for different indicators. Countries are ordered by GDP_{PPP} per capita, from highest to lowest. Rankings vary from 1 (red, higher values per capita) to 42 (green, lower values per capita). (For interpretation of the references to colour in this table legend, the reader is referred to the web version of this article.)

Country	Production: Waste	Production: Land	Production: Water	Production: Material	Production: Carbon	Footprint: Waste	Footprint: Land	Footprint: Water	Footprint: Material	Footprint: Ecological	Footprint: Carbon	PPP per capita
Luxembourg	2	31	39	39	1	2	3	1	2	1	1	1
Norway	20	9	24	2	7	9	5	10	5	15	8	2
United States	27	10	2	10	3	25	12	5	13	3	3	3
Ireland	38	14	31	3	8	21	8	13	1	8	4	4
Switzerland	11	33	35	34	29	14	16	17	20	14	17	5
Netherlands	3	41	30	31	16	4	7	4	12	7	11	6
Sweden	6	6	23	8	30	11	13	21	14	6	23	7
Canada	19	2	13	5	4	20	2	9	9	5	5	8
Austria	7	19	26	12	19	7	24	23	6	16	15	9
Denmark	23	28	9	9	9	12	15	12	7	2	9	10
Australia	25	1	1	1	2	22	1	2	3	10	2	11
Finland	4	4	20	4	11	3	6	22	4	9	6	12
United Kingdom	9	35	33	35	20	5	22	14	18	21	13	13
Belgium	5	39	22	27	14	8	10	8	10	4	10	14
Germany	10	34	28	24	13	6	21	18	19	23	14	15
Japan	8	37	41	40	18	10	29	28	31	27	20	16
France	16	24	14	26	31	15	9	15	23	20	27	17
Spain	17	16	4	18	26	23	20	7	17	19	24	18
Italy	21	32	12	32	24	18	25	16	25	22	22	19
Cyprus	32	36	40	7	15	29	35	31	16	26	19	20
Greece	30	21	3	17	5	17	11	3	8	18	7	21
Slovenia	13	17	36	11	22	13	19	26	15	17	16	22
South Korea	29	40	38	36	17	32	27	20	21	24	18	23
Czech Republic	22	26	27	13	12	26	34	34	27	13	21	24
Portugal	26	23	8	15	33	28	23	11	22	28	30	25
Malta	33	42	10	42	25	33	30	6	26	31	25	26
Estonia	18	8	42	6	6	16	14	29	11	11	12	27
Slovakia	15	22	21	29	23	24	31	27	29	32	26	28
Hungary	35	20	15	30	32	34	38	33	35	34	33	29
Lithuania	24	12	34	28	36	19	32	36	32	25	31	30
Latvia	40	7	37	22	38	30	18	37	28	12	32	31
Poland	14	27	32	20	21	27	37	41	30	30	29	32
Russia	1	3	16	16	10	1	4	24	33	29	28	33
Turkey	34	25	5	33	37	37	33	19	36	38	35	34
Mexico	39	13	17	37	39	39	28	30	38	35	38	35
Romania	36	18	6	14	35	38	36	25	24	39	37	36
Bulgaria	31	15	11	19	28	36	39	35	34	33	34	37
South Africa	28	11	25	23	27	35	26	40	40	37	36	38
Brazil	37	5	18	21	40	40	17	38	37	36	40	39
China	12	30	19	25	34	31	40	39	39	40	39	40
Indonesia	42	29	29	38	41	41	41	42	41	41	41	41
India	41	38	7	41	42	42	42	32	42	42	42	42

form on some other environmental footprints, especially carbon, material, ecological, and water footprints.

It is natural that countries specialize in production due to their own endowments, whereby the domestic pressure reflects the role of a country in a global supply chain. In contrast, footprints reflect the purchase of individuals within a country, which partially concentrate on the same commodities due to globalized consumption patterns and due to similar needs. Consequently, the resource requirements for inhabitants of countries with comparable development status do not vary substantially.

In addition, domestic technology greatly influences production-based accounts. Countries with high resource intensity of domestic production export commodities with a relatively high footprint. Taking into account global supply chains and trade tends to balance countries' production specialization and technologies, leading to an alignment of most footprint measures with GDP per capita, even if the countries' respective production-based accounts diverge. Indeed, a structural analysis of carbon embodied in trade indicates that specialization and resource intensity are about equally important in explaining carbon trade balances (Jakob and Marschinski, 2013). The result is a much more consistent ranking of countries based on their footprints per capita than on their production-based pressures per capita.

The low variance between footprint-based environmental performance indicators suggests that decoupling environmental impacts from lifestyles might be more difficult than decoupling within national boundaries. Several major environmental footprints are highly correlated with GDP. We thus need further policy options that drives a wedge not between production-based indicators and economic output, but consumption-based indicators and GDP.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2017.01.026.

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