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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).

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

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

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.