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Shifting economic activity to services has limited potential to reduce global environmental impacts due to the household consumption of labour

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Abstract

The tertiary (or ‘service’) sector is commonly identified as a relatively clean part of the economy. Accordingly, sustainable development policy routinely invokes ‘tertiarization’—a shift from primary and secondary sectors to the tertiary sector—as a means of decoupling economic growth from environmental damages. However, this argument does not account for environmental impacts related to the household consumption of tertiary sector employees. Here we show using a novel analytical framework that when the household consumption of labour is treated as a necessary and endogenous input to production, the environmental impacts of all sectors converge. This shift in perspective also exacerbates existing disparities in the attribution of environmental impact from economic activity among developed and developing economies. Our findings suggest that decoupling of economic activity from environmental impacts is unlikely to be achieved by transitioning to a service-based economy alone, but rather, that reducing environmental damages from economic activity may require fundamental changes to the scale and composition of consumption across all economic sectors.

1. Introduction

Human activity is driving a dramatic acceleration of global environmental degradation [1–3]. Decoupling economic activity from environmental impacts has been proposed as a solution, mitigating environmental damage while preserving economic growth (‘green growth’). There are two fundamental pathways to such decoupling—technological advances that reduce the quantity of resources used or wastes produced per unit of economic output (‘dematerialization’), and shifting the composition of economic activity from primary and secondary sectors to the tertiary sector (‘tertiarization’). We focus on the second of these pathways and evaluate the potential for structural change in economic activity towards

tertiary sectors to alleviate the environmental impacts generated by the global economy.

Tertiarization, or the ‘structural change hypothesis’, is a core part of Environmental Kuznets Curve (EKC) theory positing an inverted U-shaped relationship between average income and various measures of environmental quality [4]. This relationship, demonstrated by the experience of the developed nations in their transitions toward post-industrial service economies, is frequently alluded to in the context of sustainable development, offering a model pathway to grow economic prosperity while fostering environmental sustainability at the global level [5–16]. Several recent studies attribute various positive environmental trends observed in recent decades, in part, to structural change in the composition of economies and an overall shift toward services [17–20]. The environmental promise of tertiarization is premised on the ostensibly lower environmental impacts per

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unit of economic output ('impact intensity') of industries within the tertiary sector, particularly those producing knowledge-intensive services [7, 12, 21, 22]. In contrast, the agricultural and manufacturing industries are frequently identified as the most prominent culprits in the generation of environmental impacts [9, 23]. This framing can be understood as part of the broader 'green growth' narrative, influencing goals for sustainable development at the highest level, such as the United Nation's Sustainable Development Goal 8.2, to 'achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors' [24].

Here, we suggest that this perspective overlooks the role of labour in economic production. Specifically, it neglects how household consumption is a prerequisite to economic production, and hence a relevant driver of the environmental impacts of sectoral output. In practice, tertiarization occurs by increasing the number of people employed in higher wage sectors, alongside increasing consumption with rising income [25]. Both the labour intensity of production and level of household consumption vary considerably from industry to industry, and likewise between sectors of the economy. Therefore, heterogeneity of labour (and wages) should strongly influence the attribution of environmental impacts when consumption by employed persons is included in estimates of sectoral impact.

In this study, we examine the potential for reducing the environmental impacts of economic activity through tertiarization, separate from dematerialization of production or changes in the composition of demand. The inclusion of household consumption in the production supply chain of employing sectors is justified on the basis that the provision of labour is fundamental to production and wages paid to households provide the bulk of household income directed towards consumption. Therefore, labour must be included in intermediate consumption for the attribution of sectoral environmental impacts. We show that when labour is treated as an input to production, distributions of environmental impacts by sector tend to converge. Endogenizing labour as an economic input also reveals consumption in developed countries to be the dominant driver of environmental impacts—to a greater degree than is already revealed by the shift from conventional production-based accounting to consumption-based accounting [26–28]. Implementing this change within environmental impact accounting frameworks provides a more causally accurate representation of economic sectors needed to assess the potential of tertiarization for economy–environment decoupling (see section S1(stacks.iop.org/ERL/15/064019/mmedia) for further discussion).

While we acknowledge the possibility of green growth through dematerialization, it is equally plausible that economic growth will outpace reductions in impact intensity leading to rising aggregate ecological burdens, even allowing for unprecedented technological innovation [29]. Instances of decoupling growth from specific pollutants and resource inputs have been observed in the past, and some aggregate measures such as global land use and biomass consumption have plateaued. However, these achievements are typically mixed successes, for example, the substitution of wood with fossil fuels [30] has alleviated land-use impacts while exacerbating climate impacts from rising greenhouse gas emissions. When measured in terms of total material footprint, the developed world has not decoupled (from 1990 to 2008), although certain industrializing nations have exhibited relative and even absolute decoupling over the same period [31]. This experience suggests that while important uncertainties remain, the feasibility of long-term absolute decoupling of economic activity from environmental impacts cannot be taken for granted. Here, we seek to better characterize the potential for green growth through the tertiarization pathway, while acknowledging important uncertainties in future dematerialization via technological change.

2. Materials and methods

2.1. Experimental design

We perform consumption-based accounting (CBA) using the environmentally extended multi-regional input–output (EE-MRIO) model provided by the EXIOBASE 3 project [32, 33], modified to treat labour as an endogenous input to production. Labour is represented in terms of household consumption by employed persons. We aggregate 163 industries of the global economy into eight sectors describing consumption categories following Ivanova and colleagues [34], and select three common metrics representing diverse environmental impacts: greenhouse gas (GHG) emissions, water consumption, and land use. This method of 'closing' the input–output (IO) model with respect to labour allocates the environmental impacts associated with household consumption by employed persons to the economic sectors employing them, allowing for a novel accounting of consumption-based environmental impacts across economic sectors [35]. For the purposes of our study, we define tertiarization to be the structural economic change from primary and secondary sectors to the tertiary sector, measurable as an increase in the relative proportion of services to manufacturing, resource extraction, and agricultural industries.

We compare consumption-based accounts (CBA) generated from the standard 'open' (exogenous labour) and our proposed 'closed' (endogenous labour) versions of the detailed multi-region tables

with environmental extensions. To close the model, we use a method of endogenizing households into the inter-industry transaction matrix similar to that described by Miller and Blair [36]. Input–output (IO) models incorporating industry–household linkages are known as ‘semi-closed’, ‘extended’, or ‘Type-II’ models, and are commonplace in macroeconomic analysis. Our analysis extends this established technique to the allocation of environmental impacts to economic sectors across the global economy.

We use *pymrio*, an open source code package in Python designed for use with this and other environmentally extended multi-regional input–output (EE-MRIO) databases [37]. We use the industry-by-industry (*ixi*) classification scheme, which describes the global economy as 163 industries based in 44 countries and five rest of world (RoW) regions, inter-linked by industry and location. Temporal analysis is made possible by the recent addition of time series data provided in EXIOBASE 3 for the years 1995–2011. In order to compare output from different years, output in nominal terms was inflation adjusted to real Euros with 2005 as the base year.

EXIOBASE 3 contains a multitude of environmental indicators, with resource inputs and waste outputs described as both terms of raw values (‘emissions’), as well as characterized measures of impacts. We selected a small representative group of three impacts: (1) aggregate GHG emissions in units of carbon dioxide equivalents (CO₂e) using the global warming potential method with a 100-year time horizon (GWP 100), (2) total water consumption (blue water, i.e. net water use), and (3) total land use.

We employ the Leontief demand-pull transformation in two ways: open and closed with respect to labour. The first method is identical to that conventionally used to derive CBA, which we refer to as the ‘open model’. The second method involves closing the model with respect to labour, which endogenizes wages paid and the household consumption of labour into the transaction matrix (the ‘closed model’). Wages paid to employees by industry and location are inserted as rows and household consumption as columns in the global transaction matrix, while simultaneously subtracting this consumption from final demand, leaving only non-household purchases (e.g. government). This modification of conventional IO methodology follows the approach described by [38]. The corresponding closed-CBA results in an attribution of the household consumption by labour to employing industries (equivalent to adding labour as an additional branch to each step of the production supply chain; see section S5 for a more detailed explanation of this process). Impacts are derived using emissions extensions and conversion factors provided in the database.

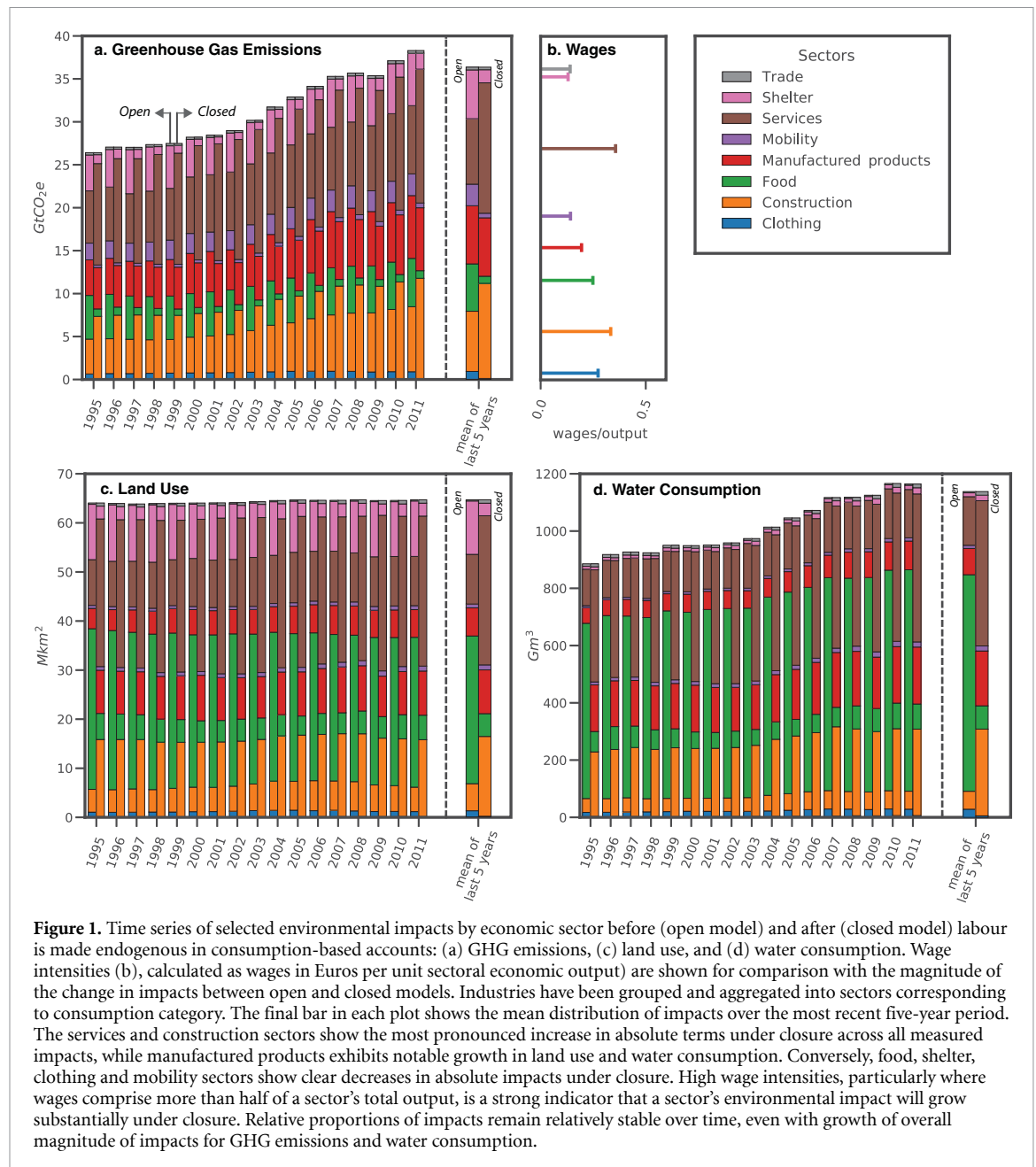
Note that we do not differentiate between employment skill levels (in practice, employees of

differing income levels, e.g. low- vs. high-skilled) within industries or sectors, since it is aggregate wages that correspond with household income that drive impacts. To clarify, when we refer to ‘high-wage sectors’, we are describing aggregate wages paid to employees of a sector, not what is colloquially understood as high individual wages (i.e. wages per worker). While salary is a reliable proxy of personal impact [39], aggregate wages are the key variable for determining total environmental impacts related to consumption [25], as studied here. It is therefore not strictly necessary to differentiate between skill levels unless one wants to know how much impact is attributable to each labour category. We consider homogenous representation of labour within industries as a valid approximation when income distributions within industries are approximately stable over time. That way, although the proportion of income saved tends to increase with rising wages, impacts per unit growth in economic output should not substantially change for incremental increases.

Industry-level data is aggregated into sectors according to the Consumption Categories outlined in the *DEvelopment of a System of Indicators for a Resource efficient Europe* (DESIRE) classification scheme (for details, see [40]). Alternative groupings can be used, and results are somewhat sensitive to the choice of grouping. The same analysis presented in the paper’s main results performed with the International Standard Industrial Classification (ISIC) scheme can be found in the Supplementary Information (figures S1 and S2). The qualitative findings of the results are largely unchanged, though constituent industries within aggregate groupings sometimes exhibit different behavior from the mean change for the grouping. See section S2 for a discussion of how aggregation classification choice affects results.

We then compare the CBA derived environmental impacts before and after model closure, to examine the change in their global distribution by sector (figure 1) and by geographic location (figure 3). Figure 1 contains annual values for the full data set of 17 years (1995–2011) and the mean of the last five years of available data (2007–2011) in an adjacent box. Wages per unit output shown in figure 1(b) are calculated as total wages for each Consumption Category divided by Final Output for the mean of the last five years, in 2005 Euros. Choropleth maps in figure 3 assume aggregated RoW regions have a homogeneous distribution of impacts, as is assumed for the distribution of measured quantities within countries. Percent change is defined as the change from open to closed models as $(closed-CBA - open-CBA) / open-CBA \times 100\%$.

We also examine the distributions of sectoral impacts before and after closure with respect to labour when normalized by output (‘impact intensity’). Box plots shown in figure 2 use whiskers with



maximum and minimum values within 1.5 IQR of the 75th and 25th percentiles, respectively. Outliers have been omitted for legibility.

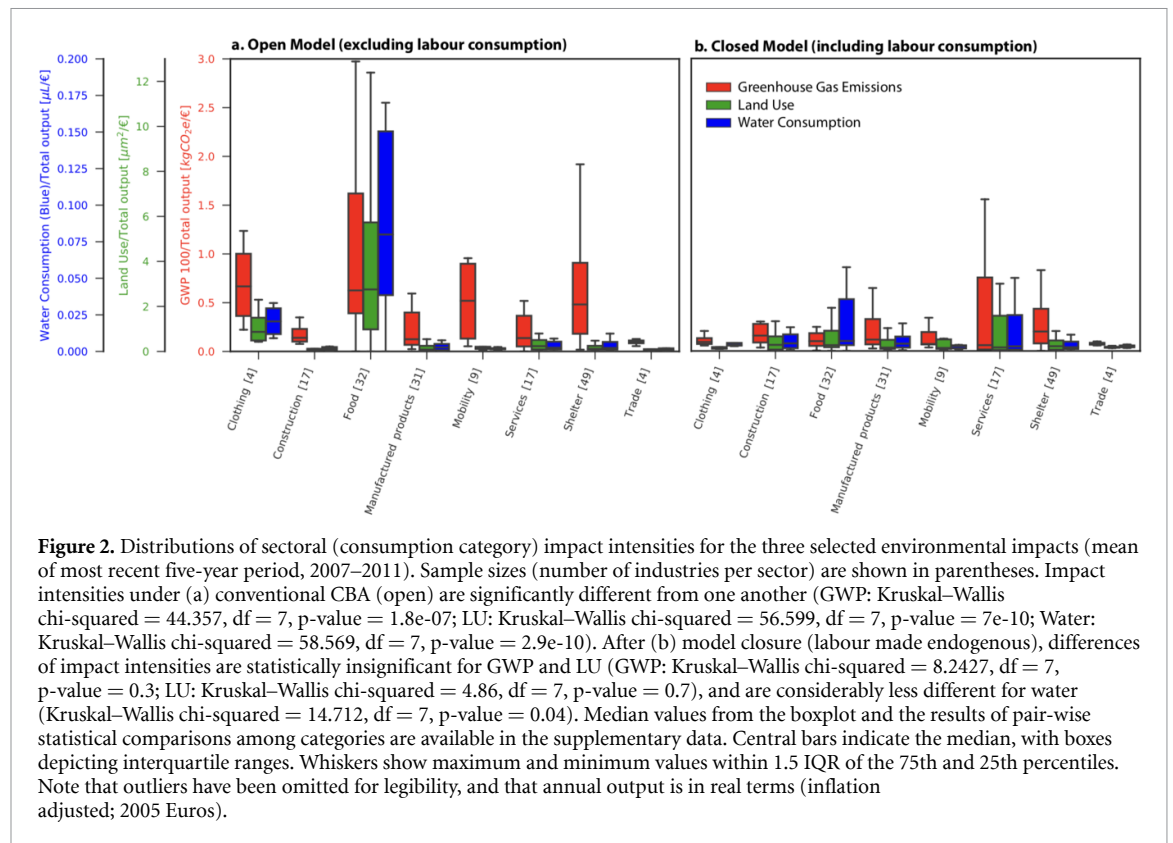
2.2. Statistical analysis

Differences in impact intensities among sectors were assessed using non-parametric tests because normal assumptions were violated. Kruskal–Wallis tests were used to compare full sets, and comparisons of individual sectors were made using Wilcoxon pairwise tests. Lastly, in all cases we have verified that all monetary and physical quantities are conserved under closure, i.e. global totals of all monetary and environmental extensions are the same for both open and closed models.

3. Results

3.1. Household consumption and global environmental impacts

The reallocation of household consumption to employing industries reveals increased absolute environmental impacts for the Service, Manufacturing and Construction sectors, with corresponding decreases in the impacts originating from the Food, Clothing, Shelter, and Mobility sectors (figure 1). We find this pattern is time invariant (1995–2011) and consistent across all selected indicators: GHG emissions (figure 1(a)), land use (figure 1(c)) and water consumption (figure 1(d)). Changes in absolute impacts from 'open' to 'closed' models are not significantly correlated with wage intensity, however, the



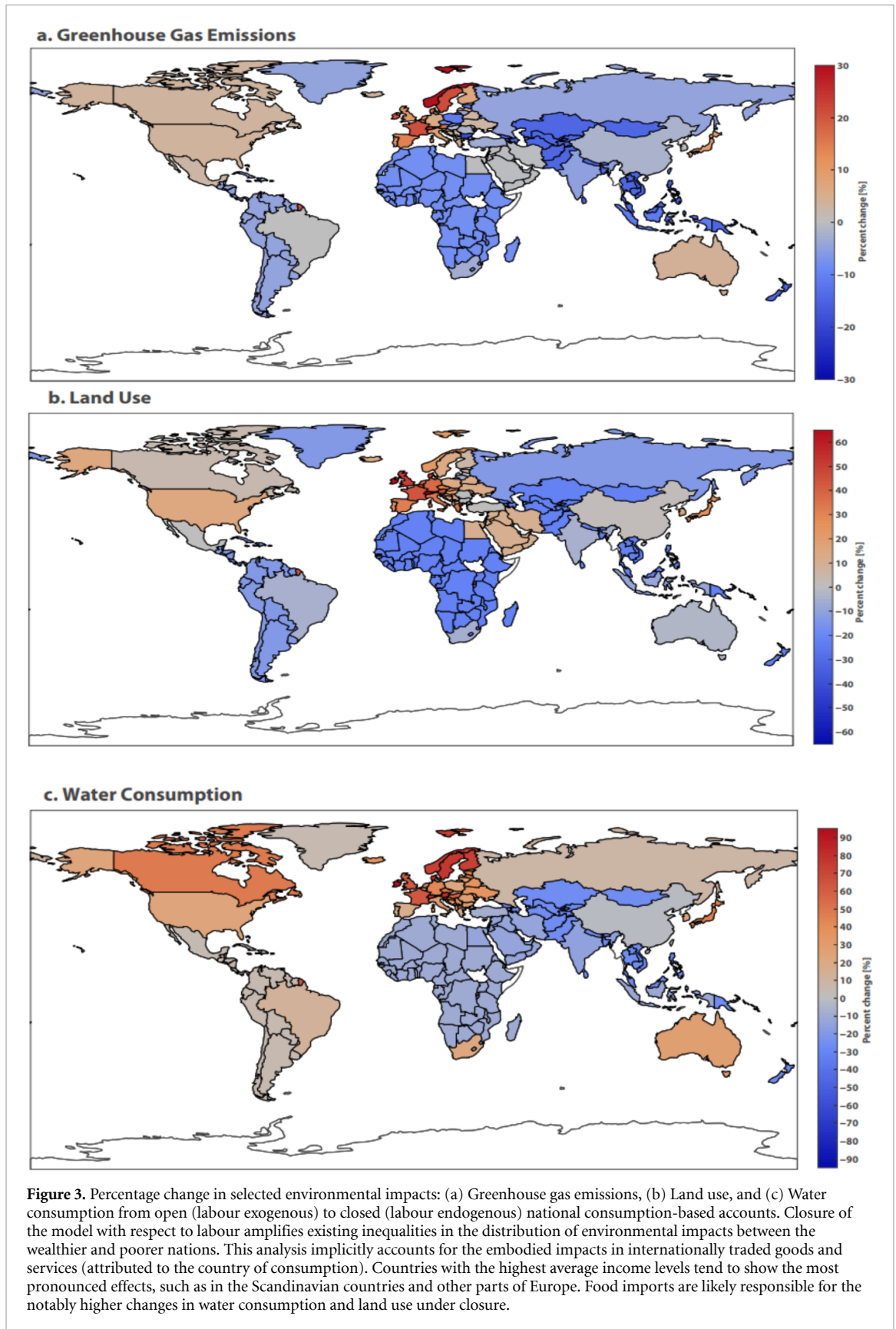
sectors where wages exceed a third of final output—Services and Construction have wages per unit production (measured in total output) of 0.36 and 0.33, respectively—exhibit marked increases in allocated impacts (figure 1(b)). By far, the largest aggregate wages paid occur within Services, which comprise 54% of total global wages annually, followed distantly by Manufactured Products with 15% of global wages (see supplementary data for summary tables of wage intensity and percentages by sector). Wages alone are insufficient predictors of impact when accounting for household consumption by employees. For example, emissions from Manufactured Products remain relatively unchanged (figure 1(a)), which suggests that increased impacts attributable to household consumption by labour in this sector are offset by impacts embodied in products consumed by labour employed by other sectors.

When examining impacts averaged over the most recent five-year period available (2007–2011), the Service and Construction sectors show the largest overall increases after closure, with increases in GHG emissions of 102% and 71%, increased land use of 213% and 203%, and increased water consumption of 208% and 394%, respectively. Impacts associated with the Food sector decrease more than any other sector consistently across all three metrics (GHG: –85%; land use: –85%; water: –90%).

The Service sector occupies the largest proportion of GHG emissions in both the open and closed models, and approximately doubles from 22% to 45%

of the global total upon IO model closure. The Service sector also rises to the top position in land use and water consumption from third and second place, respectively, rising from 15% for both to 48% and 46% shares of global totals. The Food sector falls from the top driver of both land use and water consumption in the open model to fifth place for both in the closed model (48%–4% and 68%–1%, respectively). In other words, food production is shown to be much less environmentally burdensome than conventionally thought when it is not attributed with impacts generated by consumption supporting employees working in other sectors.

Specific industries with the largest relative increases (measured in percent change) in impact after model closure are concentrated in the Construction, Manufactured Products, Service, and Shelter sectors. In the Service sector, ‘Computer and related activities’ increases by the largest amount: by 292%, 680%, and 770% for GHG emissions, land use, and water consumption, respectively. The next largest increases in industrial impacts in Services (in decreasing order) are ‘Public administration, defense and compulsory social security’, ‘Education’, and ‘Research and development’, with increases of approximately 125%–175%, 350%–550%, and 450%–650% in GHG emissions, land use and water consumption, respectively (see supplementary data for full analysis). We find up to 1100% increases in land use for industries in the Construction sector, and up to 1200% increases in water consumption for industries in



the Shelter sector. Industries with the largest relative decreases in impacts are overwhelmingly found in the Food sector, along with industries closely related to food production or food services (classified as part of other sectors), and select Clothing and Manufactured

Products industries; with some industries specific to food processing and electricity production exhibiting declines of -99.8% , -99.7% , and -99.5% of their original (i.e. open-CBA) values for GHG emissions, land use, and water consumption, respectively. Note

that these percent differences are true for absolute impacts as well as impact intensities (section 3.2).

3.2. Environmental impact intensities of sectors

We find a dramatic convergence in sectoral impact intensities when household consumption of labour is endogenized (figure 2). In the open model, differences in environmental impact intensity among sectors are statistically different for all three environmental metrics (Kruskal–Wallis: $p = 2e-7$ for GHG emissions; $p = 7e-10$ for land use; $p = 3e-10$ for water consumption), with the Food, Clothing, Mobility, and Shelter sectors showing statistically higher impact intensity than the Construction, Manufacturing, Service, and Trade sectors (Mann–Whitney pairwise comparison, $p < 0.05$, figure 2(a)). By contrast, in the closed model, sectoral differences in environmental impact intensity are generally not statistically significant (Kruskal–Wallis: $p = 0.3$ for GHG emissions; $p = 0.7$ for land use; $p = 0.04$ for water consumption), with the exception of water consumption in which the Food sector remained statistically higher per unit economic output than that of Shelter (Mann–Whitney pairwise comparison: $p < 0.05$, figure 2(b)).

Although the results show that overall, sectors do not differ significantly in their impacts, the aggregated figures mask a wide spread of impact intensities intra-sectorally. Simply said, industries within sectors do not all have the same impact. In Services, due to the heterogeneity of wages within the sector, impacts of employment vary dramatically. Intuitively, industries that employ more low-skilled labour (with correspondingly lower total wages paid) have lower impact per unit production than high-skilled, high-wage industries. For example, within Services, the closed impacts of ‘Computer and related activities’ (GHG: $0.5 \text{ kg CO}_2\text{e } \text{€}^{-1}$, land use: $0.9 \text{ } \mu\text{m}^2 \text{ €}^{-1}$, water: $20 \text{ nl } \text{€}^{-1}$) are 20 to 25 times larger than that of the ‘Hotels and restaurants’ industry ($0.02 \text{ kg CO}_2\text{e } \text{€}^{-1}$, land use: $0.04 \text{ } \mu\text{m}^2 \text{ €}^{-1}$, water: $1 \text{ nl } \text{€}^{-1}$). A full account of the open and closed impact intensities is presented in the supplementary data.

3.3. International distribution of environmental impacts embodied in trade flows

The shift from an open to closed model amplifies the allocation of environmental impacts resulting from final consumption to wealthy countries with a corresponding decrease in allocation to developing countries (figure 3). Country-level results follow sectoral patterns—countries with a high proportion of service-based industries tend to exhibit increases in impacts, while those with high proportions of primary and secondary production, such as agriculture and manufacturing, show marked decreases in impacts. When compared to the open model (which represents a typical consumption-based accounting

of environmental impacts), Scandinavian and Western European countries, Japan, and the United States show prominent increases in impacts associated with economic production, while countries in Africa, Eastern Europe, and South, Central, and Southeast Asia show notable decreases (figure 3).

In absolute terms, closed-CBA reveals China and India as the largest exporters of GHG emissions embodied in goods and services, while the United States and Japan are the largest importers for all three impacts studied. The largest exporters of embodied land use include Russia and Brazil, and the largest exporters of embodied water consumption are India and China (supplementary data). Note that the rest of world (RoW) regions exhibit declines in impacts on the same scale or higher than individual countries identified; the largest decreases in GHG emissions and land use would be by RoW Asia and Pacific and RoW Africa, respectively, if these regions are compared directly to countries.

When switching from open to closed models, annual international transfers of environmental impacts increase by approximately $3.3 \text{ GtCO}_2\text{e}$ for GHG emissions, 8.8 Mkm^2 for land use, and 170 km^3 for water consumption (using mean values for the 2007–2011 period). This represents an additional shift on top of that which occurs when moving from production- to consumption-based accounting of impacts in an open model configuration. For comparison, there are $36 \text{ GtCO}_2\text{e}$ of GHG emissions, 65 Mkm^2 of land use, and 1100 km^3 of water consumption embodied in trade from a conventional consumption-based perspective (i.e. when switching from PBA to open-CBA). In percentage terms, the total amount of GHG emissions, land use, and water consumption embodied in trade (when switching from PBA to open-CBA) has been estimated at approximately 27%, 30%, and 28% of global totals for the mean of the 2007–2011 period; consequently, the trade flows in our closed model increase to 36%, 44%, and 43% of global totals (from PBA to closed-CBA; i.e. an increase of 9, 14, and 15 percentage points, respectively, from open- to closed-CBA). Note that most of the shifts in impacts comparing open and closed models are concentrated in a small number of developing and emerging economies, and a larger number of developed ones. This pattern is broadly similar to that of GHG emissions embodied in trade when moving from production- to consumption-based accounting.

Geographic changes due to model closure are largest for water consumption (changes of up to $\pm 90\%$) followed by land use (up to $\pm 60\%$), and GHG emissions (up to $\pm 30\%$). For example, the largest increases in GHG emissions upon model closure occur in Norway (+30%), Switzerland, Luxembourg, Sweden, and France (each approximately +20%), with ‘Education’ as the largest single driving industry for all five countries (supplementary data). This

predominance of increased impacts in the high-wage service-oriented economies in northern climates is likely due to high net imports of labour-intensive goods in these countries. Over recent decades, more affluent nations have increasingly imported consumption goods from regions where labour costs are lower. Closing the EE-MRIO model with respect to labour thus exacerbates existing disparities in environmental impacts between richer and poorer nations. The shift in environmental impacts among nations that results from changing from production- to consumption-based accounting is therefore likely underestimated in conventional consumption-based accounts [27, 41].

4. Discussion and conclusions

4.1. Summary of results and comparison with previous literature

After endogenizing labour in global supply chains, we show that industries typically labelled ‘dirty’ (i.e. high impact per unit value) are not the main drivers of environmental pressures (figure 1), and are also no ‘dirtier’ than services (figure 2), which are typically thought of as high productivity sectors with low environmental burdens. Instead, we find that all sectors are roughly equivalent in terms of climate, land and water impacts per unit production (figure 3). In other words, the distributions of sectoral impacts per unit production converge, and in almost all instances, become indistinguishable from one another.

Our findings are consistent with recent research that has highlighted hidden sources of environmental impacts in the ostensibly ‘clean’ knowledge-based service industries [4, 22, 42]. This research also supports the argument that the effect of international trade can be to offshore the more impact-intensive components of global supply chains to low-wage developing countries, making the developed economies appear to be getting cleaner [10, 28, 43–46]. We show that a reallocation of impacts to account for labour and household consumption amplifies the effect of offshoring, owing to disparities in income and consumption between developed and developing nations.

We speculate that India and China are still among the largest net exporters of impacts because they are the factories of the world, though their largest workforce does not imply they have the largest purchasing power. Rich countries import more than they export, and this is compounded when labour’s upkeep is included. For example, much of the cotton grown in India is woven there or in China but ultimately is bought by affluent people in other countries, and the water embodied in it follows it there.

4.2. Assessing potential for green growth via a shift to services

The operation of any economic sector both requires and supports household consumption, which in

turn generates environmental impacts. Therefore, we argue that in order to assess the potential for green growth via a shift to services (or any other sector), one must estimate the sector’s total impact including the sector’s influence on employment and aggregate demand. We demonstrate that when the associated impacts are ascribed to the employing sectors, the scope for absolute economy–environment decoupling is considerably more limited than is typically assumed.

Based on our analysis, we argue that the environmental burden of high-wage, labour-intensive (i.e. tertiary) industries has been significantly understated. Conversely, primary and secondary industries producing significant direct impacts but with lower reliance on high-wage labour have been overemphasized in relation to their environmental impact, since the demand for products from these industries is generated by the household consumption supporting production in other economic sectors, notably in Services. Our results are in line with those of Stern *et al* [47], Henriques and Kander [48], Parrique *et al* [49], and Fix [50], all of whom note a relative lack of importance of structural economic changes for environmental outcomes.

4.3. Limitations and caveats

Limitations of our study include those inherent to all EE-MRIO analyses. For example, the precision of our estimates is limited by national data quality and inconsistencies when harmonizing data across countries. Industries are approximated as being homogenous in composition (producing a single, aggregate product), while inter-industry transaction coefficients and environmental impact coefficients are treated as constant for each year. Specific to our study, model closure with respect to labour assumes that a static proportion of income is allocated by households to consumption during a given year (i.e. static savings rates). Changes in economic structure associated with tertiarization would in fact likely raise aggregate household consumption through higher wages, but would also raise savings rates, which tend to increase alongside income. As such, aggregate impacts can be expected to grow somewhat more slowly than wages paid as a result of tertiarization. To clarify, we are interested in impacts related to household expenditures, not due to economic activity that is driven by investments (made with household savings). We acknowledge that savings may drive impacts, but we expect them to be less correlated with savings rates. We leave the verification of this hypothesis to future inquiry.

The composition of aggregate household demand can be expected to change in line with tertiarization and increased aggregate wages, with a growing level of demand for services. This change is not modeled explicitly in our closed-EE-MRIO formulation but is unlikely to invalidate our findings, as additional

service demand would typically add to, rather than substitute for, absolute demand for primary and secondary goods [49]. Rather, people tend to maintain spending on necessities like food, energy, and shelter, while simultaneously increasing their spending on services (for example, see [51]). We therefore expect that primary and secondary output would increase with a growing tertiary sector. In other words, we expect proximate economic drivers of environmental impacts to be relatively unaffected by tertiarization, barring unprecedented disruptions to trends in technological or behavioural factors in the near term, which we feel to be an acceptable assumption given the evidence provided to date. Furthermore, as our analysis shows similar levels of environmental impact intensity across sectors, the effects of modest changes in demand composition can be safely assumed to have a minor effect. Ultimately, a dynamic closed-EE-MRIO model would be required to assess the effect of more radical long-term changes in demand composition, which we leave for future study.

4.4. Possible roles of tertiarization in sustainable development

We show the effect of tertiarization on global environmental impacts to be statistically insignificant, all else being equal. However, this does not imply that tertiarization cannot play a beneficial role in sustainable development. Tertiary industries typically entail higher levels of employment and remuneration, and so we expect that impacts determined via closed-CBA will be more responsive to decreases in impact intensity (through technological improvements) and consumption levels per capita, than open-CBA, since household consumption is a primary driver of environmental impacts. If it were to occur alongside cleaner production and reductions in aggregate demand, tertiarization may augment the mitigation of environmental burdens. Conversely, this greater sensitivity means that tertiarization may exacerbate environmental impacts if household consumption continues to increase in line with historical trends.

It is important to note that dematerialization via technological changes, the first pathway mentioned in the introduction, would reduce total impacts irrespective of structural changes in economic composition. However, we are concerned that dematerialization on the scale required to achieve absolute reductions in environmental impacts may be implausible on relevant timelines [49, 52], particularly given that efficiency gains from technological improvements often translate to productivity increases rather than a reduction of the environmental impacts of production [53, 54]. As such, our results suggest that tertiarization will not help to reduce global environmental impacts or assist sustainable development without simultaneous reductions in household consumption.

To date, attempts to identify pathways towards sustainability have focused heavily on proximate, rather than structural causes of environmental pressures. The service sectors of developed economies foster higher than average material standards of living, stemming from high wages and consumption-oriented social norms. The patterns of consumption required to maintain the provision of labour, regardless of industry, face the same complex web of economic interdependencies implicated in the generation of environmental impacts. As such, increases in income (and aggregate economic output) cannot easily be reconciled with sustainable development [55–58]. Rather, our results suggest that, barring unprecedented technological innovation, the patterns of consumption behavior that currently permeate the social fabric of contemporary societies will need to change in order to alleviate the environmental harm caused by economic activity. A broader range of research perspectives should therefore be directed to assess how the United Nations' Sustainable Development Goals (SDGs) can be achieved, and notably to how we can 'create the conditions that allow people to have quality jobs that stimulate the economy while not harming the environment.' (SDG 8) [59]. Closed formulations of EE-MRIO models could also be prioritized in studies of economic change and environmental impact, and be used alongside standard IO analysis for environmental accounting more generally to better inform macroeconomic analysis and decision-making. As discussed by Ottelin and colleagues [60], the discussion of appropriate policy instruments in alignment with the broader CBA perspective is lacking. Our findings support this assessment—future research should be directed towards exploring appropriate policy instruments for the amelioration of environmental impacts stemming from economic activity while recognizing the limitations of proposed pathways for decoupling of economy and environment.

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Author contributions

This research was designed and coordinated by DHG and TC. Statistical work and additional supervision was provided by HDM Data was provided by KS All authors performed analyses, discussed the results, and wrote the manuscript.

Competing interests

The authors declare no competing financial interests.

Data and materials availability

All IO data used is publicly available from EXIOBASE at www.exiobase.eu and source code for python package *pymrio* used for conventional IO manipulations and analysis can be found at <https://github.com/konstantinstadler/pymrio>. Additional population data was taken from <https://data.worldbank.org>. Statistical analysis was performed using R software, available at www.r-project.org/. Summary data of results from the closed-IO model and other data that supports the findings of this study (supplementary data) are openly available at <https://doi.org/10.25412/iop.11936313.v1>.


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