CARBON ACCOUNTS FOR MEASURING SUSTAINABILITY UNDER GLOBALIZATION

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Abstract:

We contribute to sustainability accounting by examining three potential attribution rules, constructing a global account for each. We shift the focus from the location of emissions to the location of damages to introduce a new carbon accounting perspective that is fully consistent with: (i) sustainability theory, (ii) climate economics, and (iii) sustainability accounting for a world in which countries are not compensated for climate damages. Our approach extends the supply chain of virtual carbon flows beyond extraction, production, and consumption to incorporate the distribution of the global climate externality. We determine the distribution of these damages in two ways, using a 140 region 57-sector multi-regional input-output model (MRIO): a regional integrated assessment model with global coverage (Nordhaus & Boyer 2000); and econometric modelling of the historical relationship between GDP growth and temperature change (Burke et al 2015). Our results show that the damage based accounting approach using the former method has similar distributional implications to the production and consumption based approaches, but using the more recent method implies far more unequal outcomes, with some northern rich countries initially benefiting from warming while larger damages fall on other countries. We conclude that the observed progress towards national and global sustainability is sensitive to the accounting perspective used, suggesting that sustainability accounting requires a 'dashboard' approach combining multiple carbon accounts. The damage based approach has implications relating to the design of international climate agreements, the potential for climate compensation, and multiple Sustainable Development Goals: 8.4 (Economic Growth), 10.b (Reduced Inequality), 12 (Responsible Production and Consumption), 13 (Climate Action), 17.11 (Trade), and 17.19 (Monitoring and Accountability).

1. INTRODUCTION

Sustainability science for the 21st century must account for globalization across three domains: economies, environmental challenges, and policy needs. In the half century from 1961-2011, international trade grew from 24% to 61% of gross world product (World Bank 2018), and goods traded internationally now drive 20-25% of global CO_2 emissions (Afionis et al. 2017). Because production processes cross multiple borders along global supply chain, where we account for the associated embodied, or 'virtual' carbon flows becomes a key policy issue (Davis et al. 2011). But in failing to adequately address globalization, the carbon accounting literature is failing to reach its potential to inform sustainability theory, accounting, and policy. We place carbon accounts within a formal theory of sustainability, construct global greenhouse gas (GHGs) emissions accounts that are more consistent with economics and climate science, interrogate the resulting distributional effects, and consider policy implications.

The 'wealth theory' of sustainability emerges from the notion that future consumption depends on future productive capacity, which in turn depends on current net investment in capital (Solow 1986; Dasgupta 2001; Dasgupta & Heal 1979; Asheim 2000). Defining comprehensive, or inclusive wealth as the sum of all forms of capital (e.g. human, man-made, and natural) that comprise an economy's productive base, the theory provides a clear wealth management rule: endowing future generations with the potential to be 'at least as well of as the present' requires that comprehensive wealth is non-declining over time. Following initial empirical contributions by Pearce and Atkinson (1993), wealth accounting research seeks to measure the extent to which individual countries adhere to the capital management rule (Pearce & Atkinson 1993; Lange et al. 2018; World Bank 2006; World Bank 2011; UNU-IHDP & UNEP 2012; UNU-IHDP & UNEP 2014; Managi & Kumar 2018) (Fenichel et al. 2018).

The biosphere's capacity to regulate climate is a component of natural capital. GHG emissions degrade this capital and are reflected in sustainability accounts as wealth depletions: the marginal ton of CO_2 equivalent reduces future productive capacity by the value of the social cost of carbon (SCC). But while sustainability accounts are typically compiled at the national level, the integrated assessment models (IAMs) used to calculate the SCC and tend to be global in scope, or contain a small number of regions (e.g. RICE2010 contains 12 region)(Nordhaus 2017). An attribution rule for distributing global wealth depletions across countries is needed to measure the sustainability of individual nations, and their contributions to global (un)sustainability. This paper investigates potential attribution rules (henceforth, accounting perspectives).

A rich literature explores the motivations and implications of attributing emissions to countries at different points along the global supply chain. Four main perspectives have been proposed. *Extraction based* (EB) accounts attribute emissions to the country in which fossil fuels were extracted, regardless of where they are combusted or the resulting goods are consumed. *Production based* (PB) accounts attribute emissions to the country in which emissions in the production of goods and services, regardless of where the source fuels originated or resulting goods are ultimately consumed. *Consumption based* (CB) attribute emissions to the country in which goods and services are consumed, regardless of where they entered the supply chain or were released into the atmosphere. *Sharing based* (SB) perspectives attribute emissions according to some form of shared responsibility, such as historical emissions or value-added (ie relative gains from trade) (Marques et al. 2012; Steininger et al. 2016)(Kartha et al. 2009).

Each perspective tells us something different about an individual country's relationship to global GHG flows. More importantly, relying on any single accounting perspective creates and reinforces 'policy blindspots' (Steininger et al 2016). For instance, a PB account can identify whether domestic emissions fall following implementation of a new climate policy, but would not identify whether the decrease in domestic emissions is offset by rising imports of carbon-intensive goods (ie carbon leakage), or whether a relatively low-carbon economy could reduce global emissions at lower cost by means of technology diffusion to countries from which it imports. EB accounts also have blind spots, most notably in that they omit all non-fossil fuel GHGs. And CB accounts attribute notional liabilities for foreign production processes to domestic countries, potentially raising questions of national sovereignty. Finally, the EB, PB, and CB perspectives focus on the location of emissions, regardless of the location of damages (and therefore the wealth depletions).

We contribute to sustainability accounting by examining three potential attribution rules, constructing a global account for each, and calling for a 'dashboard approach' to emissions accounting for sustainability measurement. Shifting the focus from the location of emissions to the location of damages, we use a 140 region 57-sector multi-regional input-output model (MRIO) to introduce a new carbon accounting perspective that is fully consistent with: (i) sustainability theory, (ii) climate economics, and (iii) sustainability accounting for a world in which countries are not compensated for climate damages. The distribution of damages is determined by historical relationships between GDP growth and temperature change (Burke et al. 2015) and, for comparison, a regional integrated assessment model with global coverage (Nordhaus & Boyer 2000). Our approach extends the supply chain of virtual carbon flows beyond extraction, production, and consumption to incorporate the distribution of the global climate externality. Results show that observed progress towards national and global sustainability is sensitive to the accounting perspective used, suggesting that sustainability accounting requires a 'dashboard' approach combining multiple carbon accounts. Policy implications relate to the design of international climate agreements, the potential for climate compensation, and multiple Sustainable Development Goals 8.4 (Economic Growth), 10.b (Reduced Inequality), 12 (Responsible Production and Consumption), 13 (Climate Action), 17.11 (Trade), and 17.19 (Monitoring and Accountability).

2. Carbon accounting within a sustainability framework

Accounts are tools for telling stories over time (Coyle 2015). Ideally, the information contained in these stories is driven by the specific goals and interests of decision-making end users. Formal accounting procedures are then developed to identify, collect, and report information material to those decisions. Buried within these accounting procedures are a combination of assumptions (e.g. regarding institutional, spatial, conceptual, and temporal boundaries, and notional liabilities) and compromises (often pragmatic) that shape the way accounts can be used and the stories they can tell. Once established, accounts may be used for purposes beyond their original intent: modern national accounts were developed to assess whether the US economy could sustain a war effort, but are now (mis)used in myriad applications. A chief motivation for this paper is to examine whether carbon accounts designed to inform climate policy can tell the story of national and global sustainability.

Modern economies enable fossil fuels extracted in one country to be combusted in another to produce goods that are consumed in yet another, thus creating a global supply chain for CO_2 emissions (Fig 1) (Davis et al. 2011). A rich literature explores the motivations and implications of attributing emissions to different points along the global supply chain. The various perspectives tell different stories about national contributions to global emissions, and have important implications for assessing the efficacy and efficiency of global climate policies. In general, the literature shows that: PB accounts tend to attribute fewer emissions to wealthy industrialized nations (e.g. Western Europe) and more to developing countries with carbon-intensive exports (e.g. China); that

CB accounts do the opposite; that emissions reductions in wealthy nations (measured in PB accounts) are often offset by increased imports of virtual carbon (leakage effects, identifiable in CB accounts) from developing nations (Peters et al. 2011; Peters & Hertwich 2008); that EB accounts only cover fossil fuel emissions; that PB accounts omit transport emissions; and that CB accounts have more complete coverage, but also more error due to aggregation and data issues in trade models.

Despite these differences, the accounting perspectives share several common features. First, selection between them is arbitrary: nothing in climate science or economics compels us to adopt a given perspective, or to attribute emissions to any specific point along the global supply chain. Although PB accounts dominate global climate policy (IPCC 2006), this is more an accident of international legal norms, notions of sovereignty, and a convenient level of analysis than a scientific necessity. Indeed, it ignores a fundamental feature of climate science and key challenge for international negotiations, namely that the location of climate damages is independent of the location of GHG emissions. Second, the blind spots exhibited by each account suggest that sustainability is too complex to be fully measured from a single perspective. The multidimensional nature of national and global sustainability suggests a 'dashboard' approach might be necessary. Third, EB, PB, and CB accounts were deliberately designed to inform and evaluate carbon policy, rather than sustainability science (Fig 1). While sustainability accounts must incorporate emissions, they need not be restricted by the existence of accounts designed for other purposes. Figure 1 extends the global supply chain from extraction, production, and consumption (blue) to include the location of damages (green), thus making the sustainability account more consistent with theory (Xepapadeas et al. 2012) and science (Ricke et al. 2018).

Figure 1. Emissions accounting along global supply chains

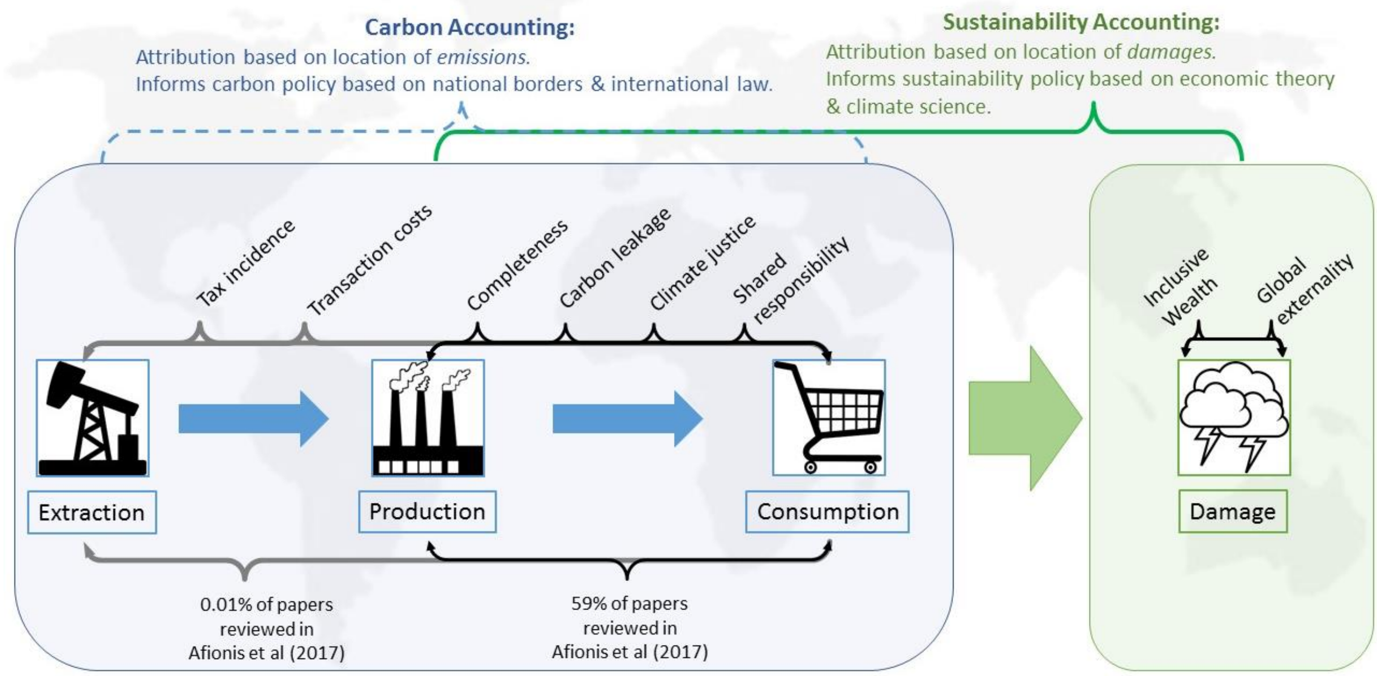

Fig 1. The global supply chain of GHG emissions from extraction to production to consumption, as characterized by the carbon accounting literature (blue) and our extension to sustainability accounting (green). The existing carbon accounting literature focuses on completeness (ie full or partial emissions coverage), carbon leakage, notions of climate justice (e.g. producer vs. consumer liabilities), shared responsibility (based on income, historical emissions, inequality, or value-added), optimal instrument (tax) design, and monitoring and transaction costs of carbon polices. The vast majority of this literature focuses on PB vs CB accounting. But for sustainability accounts, the supply chain must reflect the actual incidence of the carbon externality, as this is what determines changes in wealth. Here we 'extend the virtual supply chain' to incorporate the location of the carbon externality (damage), making the sustainability account more consistent with climate science and sustainability theory.

3. From carbon accounting to sustainability accounting

Most wealth accounts incorporate emissions according to the PB approach (World Bank 2006; World Bank 2011; Lange et al. 2018). PB adjustments to inclusive wealth accounts would be appropriate if a global compensation mechanism fully compensated countries for the damages they suffer. Absent such compensation, there is no scientific or economic justification for linking the location of emissions to reductions in comprehensive wealth (though doing so may be relevant for policy design under the polluter pays principle). Whereas the former is driven by global political and economic factors, the latter is driven by biospheric processes. There are three notable exceptions to PB wealth accounting (there are many exceptions when considering only carbon accounting). Arrow et al (2012) show formally that domestic wealth may be reduced (increased) by trans-boundary negative (positive) externalities, such as the domestic consequences of foreign emissions. The Inclusive Wealth Reports (henceforth, IWRs) (UNU-IHDP & UNEP 2012; UNU-IHDP & UNEP 2014; Managi & Kumar 2018) incorporate the potential for transboundary externalities arising from GHG emissions. Finally, Atkinson et al (2012) develop a wealth account using CB principles for emissions and other elements of natural capital.

The distinction between PB and CB accounting is important for several reasons. First, IPCC and UNFCCC carbon accounting guidance dictates that "national inventories include greenhouse gas emissions and removals taking place within national territory and offshore areas over which the country has jurisdiction" (IPCC 2006). However, this territorial boundary condition excludes the 2.6 per cent of global emissions generated by international shipping and aviation (Smith et al. 2015), which is an important part of forward looking, 21st century sustainability accounts given the growth rate of emissions in this sector (80% from 1990-2010, compared with 40% for the rest of GWP) (Bows-Larkin 2015) . Moreover, the territorial focus does not coincide with national statistics such as GDP (Pedersen & de Haan 2006; SNA 2009). However, perhaps the most important reason to consider consumption accounts is the prospect of carbon leakage when climate policies have relatively low participation. Leakage occurs when climate regulations apply unequally (e.g. more strict on developed than developing countries), thus generating an incentive for more strictly regulated economies to offshore carbon intensive activities and import carbon intensive products. Because most (60-70%) of carbon embodied in international trade is imported by wealthy countries (Hertwich, Edgar G; Peters 2008), consumption based accounts would attribute a greater share of emissions liabilities to these countries.

Shifting the focus from carbon policy to sustainability measurement, we propose an accounting perspective that adjusts wealth according to country-level damages induced by global GHG emissions. Whereas EB, PB, and CB accounts focus on the location of emissions to inform carbon policy, the damage-based (DB) perspective focuses on the location of climate impacts, as this is what ultimately drives future productive capacity, and therefore comprehensive wealth. Such accounts could be used to inform sustainability measurement, motivate adaptation strategies, assess changes in country-level comprehensive wealth, and provide insight into which countries might be compensated for climate damages.

3.1 CALCULATING COUNTRY-LEVEL DAMAGES

Empirical applications of Arrow et al's theoretical contribution require a method for calculating country level damages. The existing literature provides two such methods: disaggregating global or regional IAM results down to the country level, or using econometric models of country-level long-run (50yr) relationships between weather and GDP growth to estimate the impacts of future warming. The Inclusive Wealth Reports (IWRs) (UNU-IHDP & UNEP 2012; UNU-IHDP & UNEP 2014; Managi & Kumar 2018) adopt the first approach. We construct and report both.

The IWRs use the RICE99 IAM described in Nordhaus & Boyer (2000) to calculate country-level damage coefficients averaged over the period 1990-2010. Nordhaus & Boyer (2000) report regional damages as a percentage of GDP lost due to climate change in 13 regions under a 2.5C warming scenario. Multiplying each country's GDP by its corresponding regional damage coefficient, and dividing by the sum of damages across all regions, the IWRs calculate country-level damage coefficients. The IWRs interpret these as the percentage of global damages suffered by each country. Country-level coefficients are multiplied by the total value of carbon emissions (calculated as the product of the quantity of global emissions and the SCC) to yield country-level damages in monetary terms.

This procedure has the advantage of breaking the implicit link between the location of emissions and the location of damages. But several shortcomings remain. The first stems from its reliance on RICE-99 as a model not only of climate, but also economic change over 100 years. IAMs compound scientific unknowns surrounding climate sensitivity with economic unknowns such as the correct discount rate and the evolution of technical progress to yield results that are "close to useless for policy analysis" (Pindyck 2013). Published SCC estimates generated on the basis of IAMs vary from $-6.6/tC to $2,400/tC (Tol 2008). Moreover, IAM results are notoriously sensitive to arbitrary parameters (Pindyck 2013), which can be 'adjusted' to ensure model results are 'consistent' with what we thought we knew before using the model (Pezzey et al 2017). Finally, even as climate science progresses and provides better projections of future climate conditions, economists are left with the task of calculating the effect of these changes on economies 100 years in the future. In an important thought experiment, Schelling (1992) noted that economists in 1900 trying to do the same would have had to foresee the dominance of private cars on paved roads, widespread use of vaccines and antibiotics, internet communications, industrially produced fertilizers, and mechanized agriculture.

A second limitation of the IWR approach arises when extending regional results to the country level. RICE99 divides the world into 13 sub-regions, which for modelling purposes are aggregated to 8 regions "on the basis of either economic or political similarity" (Nordhaus & Boyer 2008 p27). Each region is described by a single social welfare function. Sectoral damage functions are common across all countries in the region. The USA and China each constitute one region, leaving six regional social welfare functions to describe the rest of the globe. The 'other high income' group lumps together Japan, Aruba, Canada, Israel, Australia, and Hong Kong. 'OECD Europe' forces Greece and Portugal into the same climate change region as Finland and Iceland. And the 'Middle income' group places South Korea, Brazil, and Barbados together in the same region. The RICE99 regions include countries that are characterized by substantial heterogeneity in terms of size, latitude, elevation, coastal extent, ecosystems, GDP, and economic structures. In using RICE-99 to break the implicit link between the location of emissions and damages, the IWR approach may have adopted a new problem in treating such diverse countries as part of the same regions.

A final and particularly important impediment to using RICE in the current analysis is that the model assumes relative autarky: there "is no international trade in goods or capital except in exchange for carbon emissions permits" (Nordhaus & Boyer 2000 p 11). Our task is to investigate how attributing emissions to different points along global supply chains informs our understanding of national versus global sustainability. It is difficult to justify an autarkic model as the basis for an accounting system to describe international trade.

3.2 The New Climate Economy Approach to Assessing Emissions

Noting the challenges and uncertainties in IAMs, an emerging literature identifies country-level economic impacts of climate change uses econometric models to estimate the effect of variation in temperature and precipitation on economic output. (Dell et al. 2014). In an early contribution, Dell et al (2012) constructed a 53 year, 125 country panel of weather and macroeconomic data to show that warming significantly reduces growth in poor countries (by 1.3 percentage points for every 1C temperature rise), but that in rich countries the effect is not robust.

Using data from 1960-2010 for 166 countries, (Burke et al. 2015) (henceforth BHM) build an econometric model to estimate the impact of changing temperature and precipitation on economic performance. Combining their model with a range of standardized future warming scenarios (Representative Concentration Pathways, RCPs)(Moss et al. 2008) and common assumptions governing the evolution of future economic and population trends (Shared Socioeconomic Pathways, SSPs) (O'Neill et al. 2014) they estimate the country-specific economic impact of future climate change. Using SSP5 and RCP 8.5 to compare a world with and without warming, BHM show a significant 22.6% shortfall in gross world product due to climate change by 2099. Globally, their results indicate much greater losses due to climate change than are predicted by leading IAMs, but at the country level, they show that currently cold countries could experience significant benefits from a warmer climate. Such results must be interpreted with caution. Numerous factors including global geopolitical responses and socio-economic tipping points could be imagined in a doomsday scenario of runaway climate change, but are not presently fit for inclusion in econometric models.

There are several advantages to using new climate-economy results in assigning carbon damages to individual countries. By focusing on macro relationships, econometric models of this sort can side-step the challenge faced by IAMs of modelling: (i) every direct mechanism whereby climate change affects economic output and (ii) the myriad indirect feedback loops between them. The availability of data at the national level avoids the complications of extrapolating from regional results, and long panels mean this approach may be better at 'capturing' country-level adaptation and changing trade relationship that may mediate climate impacts. Finally, our objective is to incorporate carbon damages arising along global supply chains within a sustainability accounting framework. Noting that accounts are only as reliable as the data on which they are built, it is helpful to use climate-economy relationships based on half a century of observed data.

4. Data and Methods

Multi-Regional Input-Output (MRIOs) models are well suited to tracing emissions along global supply chains. We use the Global Trade Analysis Project's version 9 database (GTAP9) to construct a 57-sector, 140-country MRIO[6]

[6] This is an extension over GTAPv7 used in Atkinson et al. (2012) which covered only 113 countries and regions. The list of countries and regional aggregations is available in Narayanan et al. (2015) and https://www.gtap.agecon.purdue.edu/databases/regions.asp?Version=9.211.

for the year 2011 (Narrayan et al 2015). Two chief advantages of GTAP are that it is balanced (for use at different scales of analysis) and that sectoral disaggregation is harmonized across regions. As a result, GTAP databases have become a mainstay in the carbon accounting literature (Atkinson et al., 2012; Atkinson et al., 2011; Davis and Caldeira, 2010; Davis et al., 2011; Peters et al., 2011; Proops et al., 1999).

GTAPv9 provides data on energy volumes and GHG emissions by sector and region. This includes the volume of firm and household energy purchases, as well as bilateral trade in energy products. Emissions data contained within GTAPv9 covers 28,818 million tonnes of CO_2e emissions in 2011. This includes CO_2 emissions from fuel combustion and major non-CO_2 greenhouse gasses (CH_4, N_20, CF_4, HFCs and SF_6) for the year 2011. Due to the data and labour intensity of updating non-CO_2 GHGs, these data in GTAPv9 are based on detailed raw input data for 2001 (see Rose et al. (2010a); Rose et al. (2010b) to which an emissions growth function based on EDGAR (2011) and FAOSTAT (2012) is applied (see Ahmed et al. (2014)). The decision to include non-fossil fuel GHGs imposes a trade-off: accounts that incorporate a wider range of emissions provide a more complete picture of national and global sustainability, but results will not be comparable to EB accounts constructed elsewhere (Davis et al. 2011; Steininger et al. 2016), as those studies only consider fossil fuel GHGs.

We describe a simplified (2-region, *n*-sector) version of our model below, following Miller and Blair (2009). Industry i $(i = 1, \dots, n)$ in regions r and s, produce output, x. The resulting output vectors by industry represent total supply by region. Supply equals demand as outputs become intermediate inputs z, or satisfy final demand y, which includes investment, consumption, and government expenditure. The resulting system of linear equations is described in Eq.1:

(1)
$$
\begin{matrix}
x_1^r \\ \vdots \\ x_n^r \\ x_1^s \\ \vdots \\ x_n^s
\end{matrix}
=
\begin{matrix}
z_{11}^{rr} + & \cdots & +z_{1n}^{rr} & + & z_{11}^{rs} + & \cdots & +z_{11}^{rs} & + & y_1^{rr} + & y_1^{rs} \\
\vdots & \ddots & \vdots & & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\
z_{n1}^{rr} + & \cdots & +z_{nn}^{rr} & + & z_{11}^{rs} + & \cdots & +z_{11}^{rs} & + & y_n^{rr} + & y_n^{rs} \\
z_{11}^{sr} + & \cdots & +z_{1n}^{sr} & + & z_{11}^{ss} + & \cdots & +z_{1n}^{ss} & + & y_1^{sr} + & y_1^{ss} \\
\vdots & \ddots & \vdots & & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\
z_{n1}^{sr} + & \cdots & +z_{nn}^{sr} & + & z_{n1}^{ss} + & \cdots & +z_{nn}^{ss} & + & y_n^{sr} + & y_n^{ss}
\end{matrix}
$$

Equation system (1) describes trade interactions[7] between regions and industries, and can be rewritten as Eq.2:

(2) $$\begin{pmatrix} \mathbf{x}^r \\ \mathbf{x}^s \end{pmatrix} = \begin{pmatrix} Z^{rr} & Z^{rs} \\ Z^{sr} & Z^{ss} \end{pmatrix} + \begin{pmatrix} \mathbf{y}^{rr} + \mathbf{y}^{rs} \\ \mathbf{y}^{sr} + \mathbf{y}^{ss} \end{pmatrix}$$

Technical coefficients, a_{ij} describe the ratio of intermediate input, *z* to output, *x*, and form the basis of input-output analysis. Domestic, a_{ij}^{ss} and a_{ij}^{rr}, and interregional technical coefficients, a_{ij}^{rs} and a_{ij}^{sr}, are described by Eq.3 and Eq.4, respectively:

(3) $$a_{ij}^{ss} \equiv z_{ij}^{ss} / x_j^s \quad ; \quad a_{ij}^{rr} \equiv z_{ij}^{rr} / x_j^r$$

(4) $$a_{ij}^{sr} \equiv z_{ij}^{sr} / x_j^r \quad ; \quad a_{ij}^{rs} \equiv z_{ij}^{rs} / x_j^s$$

These technical coefficients reflect the amount of industry input *i* required to produce one unit of output x_j in region *r* (or *s*), taking into account the input precedence as well as the place where the output is produced (Miller & Blair 2009). Rearranging Eq3 and Eq4, and combining with Eq2, provides regional output in terms of domestic and interregional technical coefficients, Eq5:

(5) $$\begin{pmatrix} \mathbf{x}^r \\ \mathbf{x}^s \end{pmatrix} = \begin{pmatrix} \mathbf{A}^{rr} & \mathbf{A}^{rs} \\ \mathbf{A}^{sr} & \mathbf{A}^{ss} \end{pmatrix} * \begin{pmatrix} \mathbf{x}^r \\ \mathbf{x}^s \end{pmatrix} + \begin{pmatrix} \mathbf{y}^{rr} + \mathbf{y}^{rs} \\ \mathbf{y}^{sr} + \mathbf{y}^{ss} \end{pmatrix}$$

Expressing the outputs as a function of the final demands, and the regional and interregional technical coefficients, the solution of the system in the matrix notation is shown in Eq.6:

(6) $$\begin{pmatrix} \mathbf{x}^r \\ \mathbf{x}^s \end{pmatrix} = \left(\begin{pmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{pmatrix} - \begin{pmatrix} \mathbf{A}^{rr} & \mathbf{A}^{rs} \\ \mathbf{A}^{sr} & \mathbf{A}^{ss} \end{pmatrix} \right)^{-1} * \begin{pmatrix} \mathbf{y}^{rr} + \mathbf{y}^{rs} \\ \mathbf{y}^{sr} + \mathbf{y}^{ss} \end{pmatrix}$$

[7] Note that exports from *r* to *s* are conceptually equal to imports of *s* from *r*. In practice, the statistics tend to differ not only due to transport and taxes, but also due to innate discrepancies in trade statistics. For the present study we employed export data, as this generally represents quantities traded more reliably-

Rewriting (6) once again in block matrix notation and multiplying the final demands of each region by the well-known Leontief inverse Eq.7 is obtained:

(7) $$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}^{\bullet r} + (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}^{\bullet s}$$

where *(I-A)*$^{-1}$ provides information about the direct and indirect output changes across regions and industries due to changes in the final demand in *r* or *s*. Vectors $y^{\bullet r}$ and $y^{\bullet s}$ represent the 'total' final demand - domestic plus imports - of region *r* and *s* respectively. Notice that $(I - A)^{-1} y^{\bullet r}$ accounts for the change in production (*x*) in both regions due to a change in the final demand of *r*. The interpretation is similar for region *s*.

The model is additionally extended to environmental impacts linked to the changes in production which are induced by the final demand in one specific region –'*s*' or '*r*'. We study carbon emissions across sectors and regions, denoted here as '*k*'.

Pre-multiplying both sides of Eq.7 by a diagonalized carbon intensity vector, $\hat{f}^k$, describes the ratio of carbon emissions to output by sector and region. The pre-multiplication of the diagonalized intensity vector, $\hat{f}^k$, and the Leontief inverse, (I-A)$^{-1}$, yields resource multipliers, i.e. the total, direct and indirect, increase in emissions among industries and regions due to a change in final demand in region *r* (or *s*). The resulting formulation is shown in Eq.8:

(8) $$\mathbf{f}^{k*} = \hat{\boldsymbol{f}}^{\boldsymbol{k}}\mathbf{x} = \hat{\boldsymbol{f}}^{\boldsymbol{k}}\,(\mathbf{I} - \mathbf{A})^{-1}\boldsymbol{y}^{\cdot r} + \hat{\boldsymbol{f}}^{\boldsymbol{k}}\,(\mathbf{I} - \mathbf{A})^{-1}\boldsymbol{y}^{\cdot s}$$

where $\mathbf{f}^{k*}$ is the vector of total emissions across regions due to the consumption in $y^{\bullet r}$ and $y^{\bullet s}$.

4.1 Carbon Prices

The carbon price used in sustainability accounting should reflect the full social cost of carbon, defined as the discounted value of all future (net) damages arising from emitting a unit carbon today. However, despite considerable debate of what the SCC might be (Stern et al. 2006; Tol 2008; van den Bergh & Botzen 2014; Ricke et al. 2018; Nordhaus 2017) a globally agreed value for carbon emissions remains elusive. Nordhaus (2017) uses DICE to calculated a SCC of \$31/tCO_2 (Nordhaus 2017). Averaging results from multiple IAMs, the US Interagency Working Group on the Social Cost of Greenhouse Gases produced SCC values ranging from \$11/tCO_2 to

\$105/tCO_2, with variation due to different discount rates and treatment of low-probability, high-impact events (IAWG 2016). A survey of expert economists and climate scientists resulted in mean estimates between \$150-\$200/tCO_2 (Pindyck 2016), and a recent study of SCC estimates based on BHM records a global median SCC of \$417/tCO_2 (Ricke et al. 2018).

The variation in SCC estimates is especially problematic for sustainability measurement as accounts could easily be dominated by carbon, thereby giving less weight to other elements of natural capital (Agarwala et al., 2014). Our primary interest is in the attribution of emissions and the distribution of their damages. As such, we present results as country-level attribution coefficients for PB, CB, and DB accounting perspectives, interpreted as the share of global emissions attributed to each country under each accounting perspective. Country-level attributions in monetary terms for each accounting perspective may be calculated as follows. Multiply the quantity of global emissions by a chosen carbon price to obtain the global monetary carbon liability. Multiply this global liability by the country attribution coefficient corresponding to the desired accounting perspective. In addition to country-level attribution coefficients, we report monetary values calculated in this manner, using SCC estimates of \$31/tCO_2, \$150/tCO_2, and \$417/tCO_2 for comparability.

4.2 Assigning damages to countries

We use two approaches to assign climate damages to individual countries. First, we extrapolate from the RICE99 IAM down to the GTAPv9 regional level as in the IWRs, for comparability. For example, RICE99 results indicate that OECD Europe loses 2.83% of GDP under a 2.5C warming scenario. Second, we use BHM's central estimates of country level climate impacts under SSP5 and RCP8.5. The difference between GWP in a warming world relative to the baseline is the BHM global climate liability for a given year. Country-level damage coefficients are defined as the ratio of any individual country's shortfall to the global total and indicate the proportion of global damages suffered by individual countries. Country-level damage coefficients averaged over 25 and 50-year slices of BHM results are also constructed. Finally, these are aggregated to match the 140 GTAPv9 regions. Negative damage coefficients represent country-level net benefits from climate change

5. Results

An important question is whether the various accounting perspectives described above provide differ meaningfully. If each perspective told a similar story then using PB accounts that are already compiled for carbon policy may be sufficient. If, however, the various perspectives illuminate different features of the carbon wealth of nations, then reliance on any single perspective would leave policy makers systematically underinformed.

Table 1 shows summary statistics of country-level GHG attribution coefficients calculated under PB, CB, and four variants of DB accounting procedures, using an integrated assessment model (DB-IAM), and Burke et al (2015) country-level climate impact estimates for 2011, and averaged over 25 and 50 year horizons (BHM_{2011}, BHM_{25yr}, and BHM_{50yr}, respectively) to calculate country-level coefficients. PB & CB coefficients exhibit a zero lower bound and are right-skewed (PB 7.44, CB 6.95): no country in the sample produces or consumes negative emissions. PB (CB) coefficients have standard deviation of 2.68 (2.48) and maximum value of 25.13 (20.80), in both cases, for China.

Each variant of DB accounting reflects some negative damages (gains) from warming. The IAM based results have the lowest standard deviation (1.93) and range (-0.74 to 12.65). The lower variance may be due to structural factors of the RICE99 IAM, rather than the result of climate science or economic effects. Aggregation to just 8 modelling regions means that heterogeneous biomes and economies are modelled to experience homogeneous climate impacts. DB coefficients calculated according to BHM results for 2011 and the 25 and 50 year horizons exhibit the highest standard deviation (9.47, 6.35, and 4.60, respectively), and greatest range (BHM_{2011}: -42.38 to 34.78; BHM_{25yr}: -25.23 to 27.75; BHM_{50yr} -16.53 to 25.04). Skewness also rises from -0.61 (2011) to 1.05 (50yr) as the time horizon is extended, reflecting greater losses from extreme warming.

Table 1. Summary of Attribution Coefficients (% of Global Damages)

	N	Mean	St. Dev	Variance	Min	Max	Skewness
Production Based	140	0.71	2.68	7.16	0.00	25.13	7.44
Consumption Based	140	0.71	2.48	6.16	0.00	20.80	6.95
Damage Based (IAM)	138	0.70	1.93	3.72	-0.74	12.65	4.03
Damage Based (BHM 2011)	134	0.75	9.47	89.67	-42.38	34.78	-0.61
Damage Based (BHM 25 yr)	134	0.75	6.35	40.33	-25.23	27.75	0.17
Damage Based (BHM 50 yr)	134	0.75	4.60	21.12	-16.53	25.04	1.05

Table 1. Summary statistics of country-level attribution coefficients under each perspective. PB and CB coefficients have similar variance, range, and skew, and a 0-lower bound. Four variants of damage based coefficients are calculated using the

RICE99 integrated assessment model (DB-IAM), and results from Burke et al (2015) for the year 2011, and averaged over 25- and 50-year horizons. DB-IAM coefficients exhibit smallest variation and range, DB-BHM coefficients, the largest (but falling as time horizon is extended).

Table 2 highlights (dis)agreement between accounting perspectives. Pearson correlation coefficients shows strong and statistically significant correlation r = .99 between PB & CB, and 25 year slices of the BHM variants (BHM_{2011} & BHM_{25yr} and BHM_{25yr} & BHM_{50yr}). Correlation between BHM coefficients over 50 years (BHM_{2011} and BHM_{50yr}) are also significant and strong r = .97. Interestingly, correlations between DB-IAM and the suite of DB-BHM coefficients are the smallest, r = -0.09, -0.04, and 0.04 (for BHM_{2011} , BHM_{25yr}, BHM_{50yr}, respectively), though none of these is statistically significant. DB-IAM is weakly (though significantly) correlated with both the PB and CB approaches r = 0.32 and 0.39, respectively. Finally, the BHM correlation coefficients with both PB and CB are positive, significant (except for PB and BHM_{2011},) and strengthen as the time horizon rises.

Table 2. Correlations between emissions accounting approaches

	Production Based	Consumption Based	Damage Based (IAM)	Damage BHM (2011)	Damage BHM (25 yr)	Damage BHM (50 yr)
Production Based	1.00					
Consumption Based	0.99*	1.00				
Damage Based (IWR)	0.32*	0.39*	1.00			
Damage BHM (2011)	0.21	0.23*	-0.09	1.00		
Damage BHM (25 yr)	0.26*	0.29*	-0.03	0.99*	1.00	
Damage BHM (50 yr)	0.31*	0.34*	0.04	0.97*	0.99*	1.00

Table 2. Correlations between emissions accounting approaches. Reports pairwise Pearson correlation coefficients of country-level attributions under PB, CB, and four DB accounting perspectives: following the IWR approach (for comparability), and using Burke et al (Burke et al. 2015) results for 2011 and 25 and 50 year averages, respectively. * indicates significance at the 0.01 level.

Figure 2 illustrates these relationships graphically, plotting country-level attribution coefficients for each possible pair-wise comparison of accounting perspectives. In the bottom right, BHM variants are highly correlated. In the top left, PB and CB tell a similar story. No discernable relationship may be identified between DB-IAM and DB-BHM. Importantly, the PB and DB perspectives do not appear to 'agree' with any of the DB variants, leading us to conclude that DB accounts may illuminate elements of the carbon wealth of nations that are not readily apparent in standard accounts.

Figure 2. Comparison of country-level attribution coefficients.

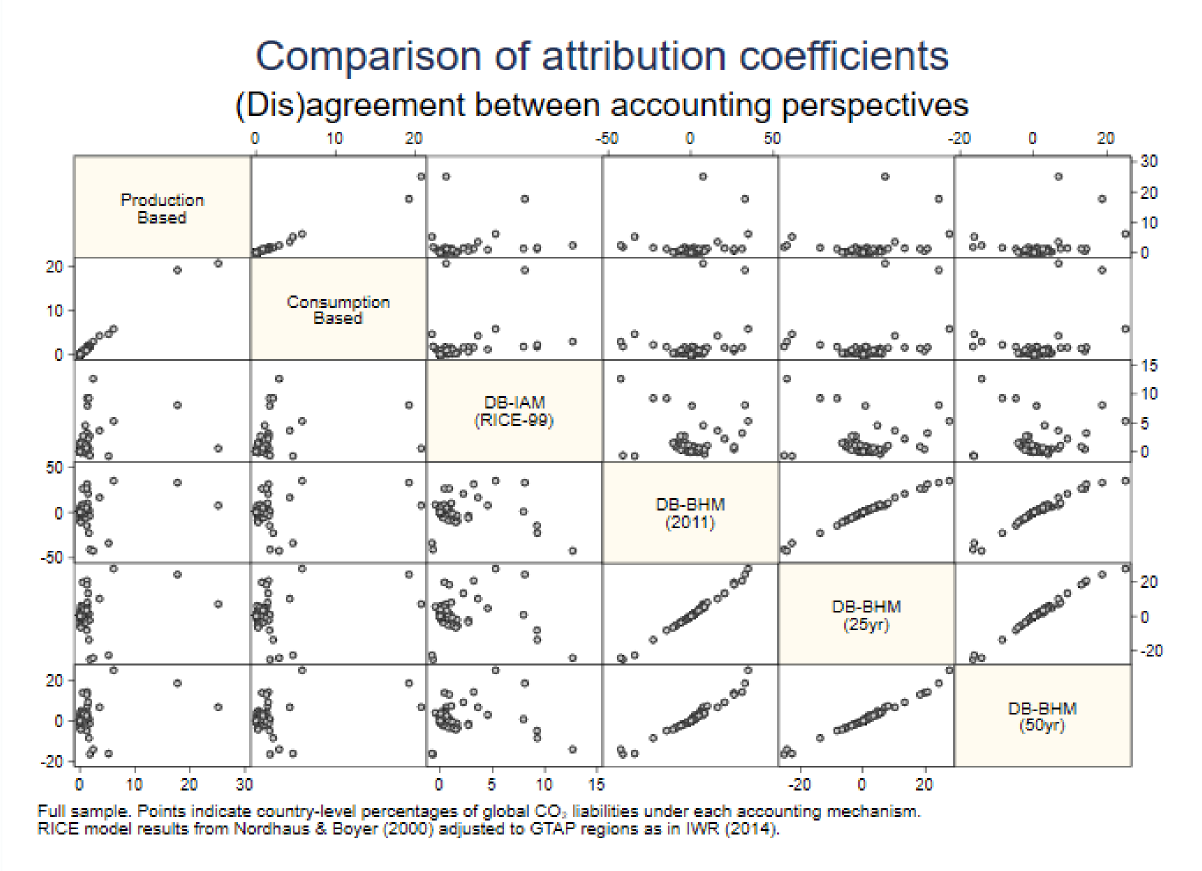

Figure 2. Comparison of country-level attribution coefficients across all accounting perspectives. Displays correlation between the various accounting mechanisms, using the full sample. DB-IAM: Damage Based – Integrated Assessment Model, using RICE99 results reported in Nordhaus & Boyer (2000), aggregated to GTAPv9 regions as in IWR (2014). DB-BHM*: Damage Based using Burke et al (2015) country-level climate impacts for the year 2011, and averaged over 25 and 50 year slices of BHM modelling.

Figure 3 indicates where (dis)agreement between perspectives arises. Splitting the sample geographically shows that there is generally agreement in most regions, with the strong exception of Europe and Central Asia. Disagreement between DB accounting mechanisms is largely driven by how they treat Europe, where strong negative correlations exist between DB-IAM and DB-BHM$_{2011}$ (Fig 5, Europe & Central Asia). There's more agreement between the DB-IAM and DB-BHM approaches in Latin America & Caribbean, Sub-Saharan Africa, South Asia. Disagreement over Europe & Central Asia is due to the fact that BHM results indicate greater benefits to mild warming across northern Europe.

Figure 3. Attribution coefficients by region.

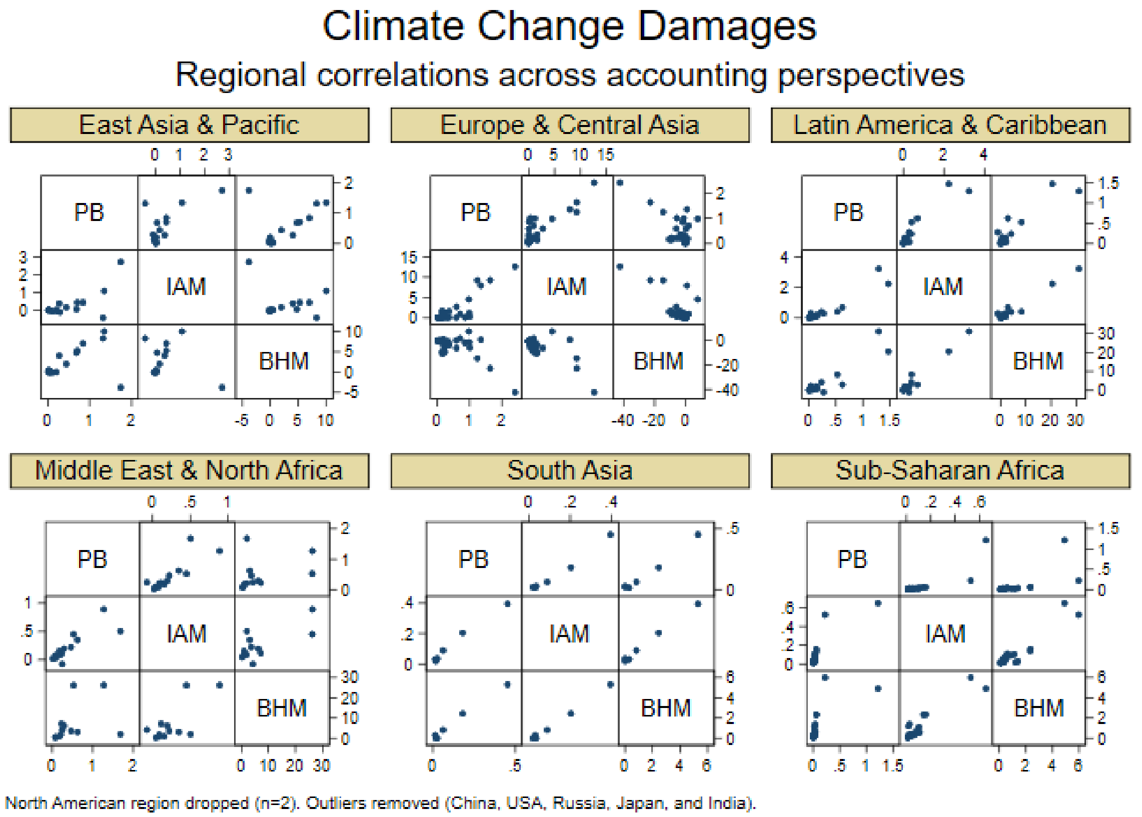

Figure 3. Comparisons of country-level attribution coefficients across different accounting perspectives. PB: Production Based accounts. IAM: damage based accounts, using the RICE99 integrated assessment model to identify country-level impacts as in IWR (2014). BHM: damage based accounts, using Burke et al (2015) results to identify country level impacts for the year 2011. For simplicity, CB and the 25- and 50-year slices of the BHM coefficients are omitted. Fig 2 shows that correlations between CB & PB, and between BHM_{2011} , BHM_{25yr}, and BHM_{50yr}, are so strong that no information is lost in this simplification. North American region is omitted (n=2). Outliers removed (China, USA, Russia, Japan, and India).

5.1 Cross-country Comparisons

Table 3 compares country level attribution coefficients constructed according to each accounting perspective for the 20 largest economies in 2011 (column 2: GDP in millions of 2011 USD). PB and CB accounts (columns 3 and 4, respectively) have been converted into coefficients describing each country's share of the total global burden, for comparison. Columns 5-8 show country-level damage coefficients under four variants of the DB accounting perspective: the IAM approach (as in the IWRs), and the BHM-based approach for the year 2011, and averaged over 25 and 50-year time scales, respectively. We deliberately do not show results over the 100 year time scale Economic projections over such time scales can at best be considered meaningless, or worse, mistaken as meaningful.

Table 3. Attribution coefficients for selected countries under different accounting perspectives

		Percentage of global damages attributed to each country					
	GDP*	Production Based	Consumption Based	Damage Based			
				IAM	BHM 2011	BHM 25yr	BHM 50yr
United States	15517.93	17.72	19.26	8.10	32.81	24.35	18.69
China	7572.55	25.13	20.80	0.59	7.50	7.14	6.79
Japan	6157.46	3.57	4.25	3.64	16.31	10.26	6.73
Germany	3757.70	2.41	2.92	12.65	-42.38	-24.34	-14.18
France	2862.68	1.24	1.71	9.26	-14.58	-8.26	-4.85
United Kingdom	2619.70	1.63	2.17	9.29	-22.71	-13.70	-8.52
Brazil	2616.20	1.29	1.59	3.23	31.10	20.72	14.34
Italy	2276.29	1.35	1.74	7.97	0.74	0.81	0.81
Russian Federation	2051.66	5.22	4.64	-0.74	-33.91	-22.71	-16.23
India	1823.05	6.15	5.82	5.31	34.78	27.75	25.04
Canada	1788.65	1.82	1.78	-0.64	-41.03	-25.23	-16.53
Spain	1488.07	0.98	1.10	4.55	7.59	4.65	2.99
Australia	1390.56	1.32	1.38	-0.42	8.31	5.58	3.90
Korea, Rep.	1202.46	1.74	1.62	2.72	-3.83	-2.38	-1.39
Mexico	1171.19	1.47	1.54	2.24	20.52	13.40	9.22
Netherlands	893.76	0.59	0.58	2.72	-6.16	-3.55	-2.09
Indonesia	892.97	1.34	1.48	1.09	10.05	8.04	7.33
Turkey	832.55	0.99	1.16	1.19	-1.34	-0.77	-0.38
Switzerland	699.58	0.14	0.32	1.68	-9.47	-5.67	-3.52

Saudi Arabia	671.24	1.27	1.33	0.89	26.23	18.36	13.00

* billions of 2011 USD. IAM refers to the RICE99 integrated assessment model. Country level GHG attribution coefficients for the 20 largest economies in 2011. GDP reported in billions of 2011 USD. Coefficients are percentages of the global GHG liability attributed to each country under each accounting perspective. Columns 3-4 report PB and CB coefficients, respectively. Columns 5-8 report DB coefficients based on IWR (using RICE99 and averaged over 1990-2010 for comparison with IWRs) and BHM results for 2011, and averaged over 25 and 50-year time horizons, respectively. Negative values indicate net benefits from climate change. Coefficients can be multiplied by total emissions (28,818 million tons in GTAPv9 for the year 2011), or by total emissions and SCC for comparison with other research.

Consistent with previous research, our results show that the US and China are dominant outliers under both the PB and CB accounting perspectives, representing a cumulative 42.85% and 40.06% of global emissions, respectively. DB accounts tell a different story. IAM-DB (column 5) are mostly positive (except for Russian Federation, Canada, and Australia), and with absolute value ≤ 12.65. In contrast, BHM-DB coefficients are negative for 9 of 20 of the world's biggest economies in 2011 and the maximum absolute value is more than three times larger, at 42.38. BHM coefficients become less extreme as the time horizon is extended, reflecting that gains from moderate warming are eventually outweighed by damages at more extreme temperatures.

5.2 Production versus Consumption Based Accounts

Figure 1 showed that the carbon accounting debate largely focuses on the distinction between PB and CB approaches (Afionis et al 2017). Table 2 and Figure 2 suggest a degree of agreement between PB and CB accounts. But Figure 4 shows the 20 economies with the greatest difference between PB and CB accounts, in millions of tons of CO_2. Positive values indicate that PB emissions are greater than CB emissions, and the region is a net exporter of virtual carbon. Negative values indicate that CB emissions are greater than PB emissions, and the region is a net importer of virtual carbon.

Figure 4. Production minus Consumption Based Emissions

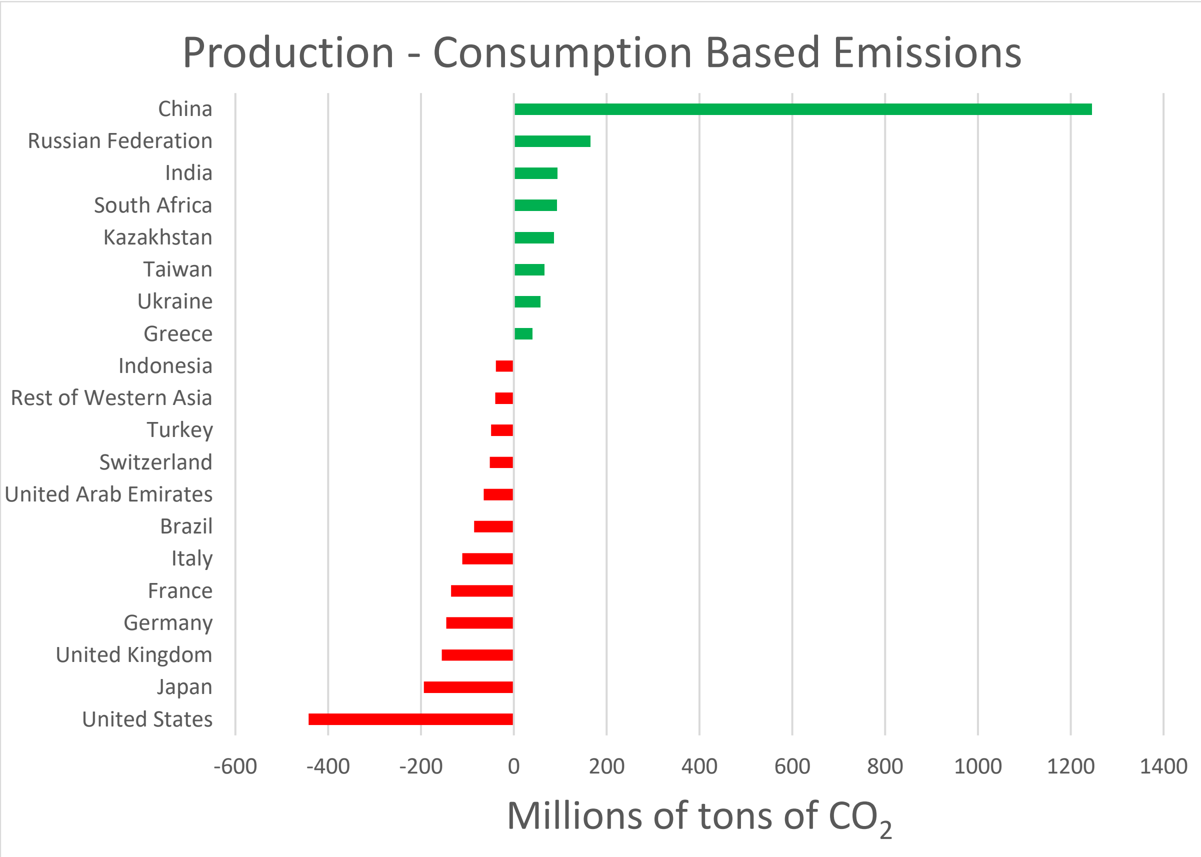

Figure 4. The 20 countries with the greatest absolute value difference between PB and CB emissions. Values in millions of tons of CO_2 for 2011. Rest of Western Asia includes Iraq, Lebanon, Occupied Palestinian Territory, Syria, and Yemen. Positive (negative) values indicate the country is a net exporter (importer) of virtual carbon. Can be converted to monetary accounts using an appropriate SCC estimate.

Our results confirm that when considering the contributions of individual countries to global (un)sustainability, the distinction between PB and CB accounts is minor. For the median country, the absolute value of the difference between (PB – CB) emissions is 5.8 million tons of CO_2, which is approximately 0.02% of global emissions, or roughly equivalent to the PB emissions of Senegal. But when considering country-level accounting, the distinction is important: for the median country, the absolute value of PB minus CB emissions represents 23% of PB emissions. Moreover, the countries in Fig. 4 represent approximately 3.3 billion people, (48% of global population), and 78% (3.36 Gt) of the world's total GHG emissions embodied in international trade (virtual carbon). Thus, for measuring global sustainability, the PB versus CB distinction is of minor consequence. Indeed, they cover approximately the same quantity of emissions (with the caveat that PB accounts omit international shipping and aviation emissions). But for accounting at the country level, and for understanding the nature of national contributions to global emissions, the distinction can be meaningful.

Figure 5 maps PB (Fig 5a) and CB (Fig 5b) coefficients for the full sample, using the same scale (note that intervals are the same for panels **a** and **b**, but that within panels the intervals are of unequal range). In both perspectives, China, the USA, India, Russia, Japan, and Canada are dominant. Europe's share of global emissions appears lower in PB accounts relative to CB accounts, confirming that Europe is a net importer of virtual carbon.

Figure 5a: Country-specific shares of global emissions under production based accounting

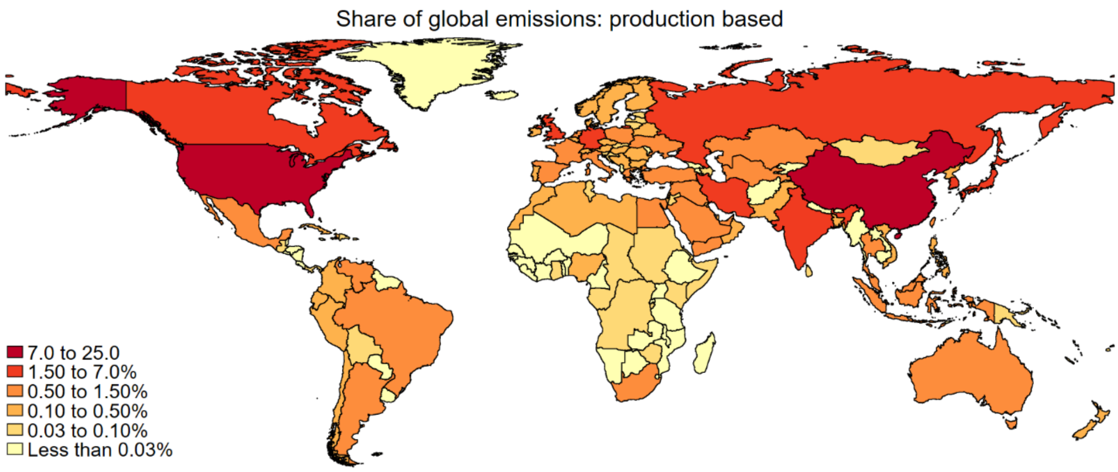

Figure 5b. Country-specific shares of global emissions under consumption based accounting

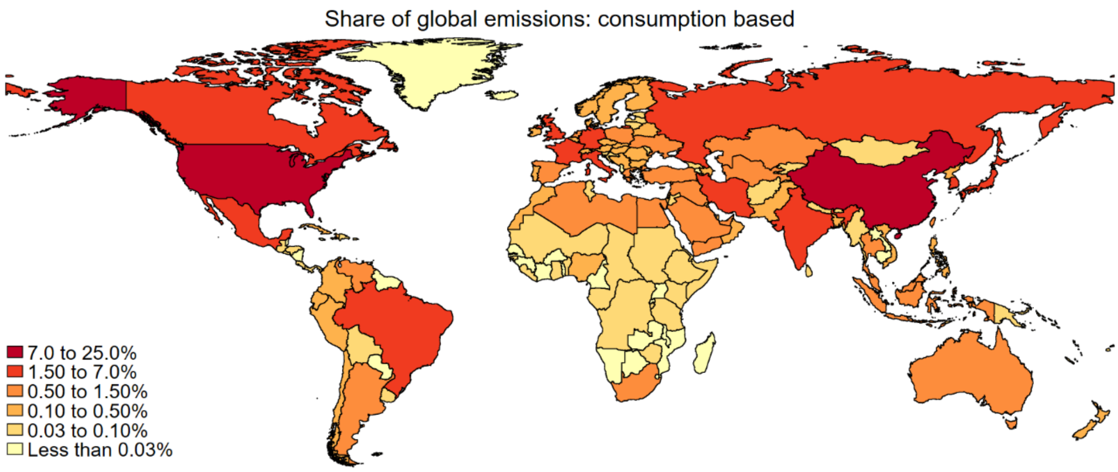

Figure 5. Country-level attribution coefficients under PB (a) and CB (b) accounting perspectives. Both perspectives exhibit 0-lower bound. Both versions are dominated by a small number of outliers. Full sample, n = 140 regions (as in GTAPv9). Country-level coefficients represent the share of global emissions attributable to each country under each accounting perspective. Intervals are the same for panels **a** and **b**, but within panels the intervals are of unequal range.

5.3 Damage Based Accounts

Figure 6 maps country level damage coefficients calculated according to Burke et al (2015) for the year 2011. These coefficients incorporate the country-level loss of production capacity and are subsequently theoretically most consistent with the capitals theory of sustainability. Under the BHM model, currently cold northern countries experience negative damages (benefits) to mild warming. The range [-42.0 to + 35.0] is much greater than for PB and CB emissions, indicating the extreme heterogeneity of climate impacts and subsequent sustainability (wealth) effects across countries.

Figure 6. Country-specific shares of global emissions under damage based emissions (BHM 2011)

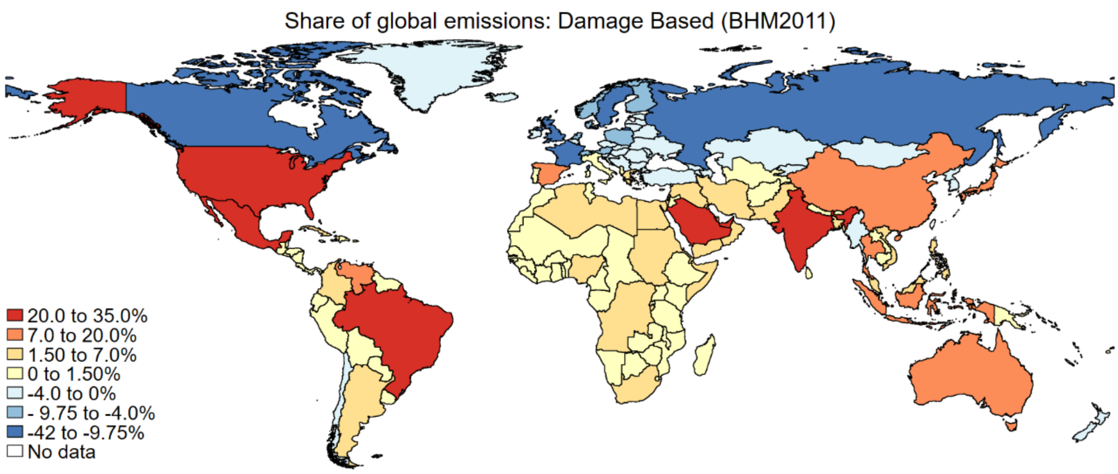

Figure 6 shows country-level GHG attribution coefficients calculated according to the BHM2011 variant of damage based accounts. Negative damages (blue) are modelled benefits from mild warming. Impacts are aggregated to match the 140 regions contained in GTAPv9 for comparison with other results.

The countries with the greatest magnitude difference between DB-BHM2011 and PB emissions include Germany, Canada, and the Russian Federation, whose economies are expected to benefit from mild warming, and Brazil, India, and the United Arab Emirates, who are expected to suffer damages disproportionate to their PB emissions. For instance, at 372 million tons of CO_2, Brazil's PB emissions represent just 1.3% of the global total, but the DB account reveals that it suffers 31.1% of the global loss of wealth due worldwide emissions from 2011. Similarly, India contributes 6.15% of global emissions (1,771.3 million tons of CO_2) under the PB account, and suffers 34.78% of the value of global damages. At the global scale, some of these extreme damages are balanced by modelled gains. For instance, the long-run, observed, functional relationship between temperature and GDP growth derived in BHM indicates that Germany and Canada are expected to experience benefits equivalent to 42.4% and 41.0% of the global GHG liability from 2011, respectively.

5.4 Distributional Implications

One of the most important implications of constructing GHG accounts from multiple perspectives is the ability to understand the distributional impacts of emissions from multiple angles. Figure 7 illustrates the unequal distribution of 'notional liabilities' for GHG emissions across the global population by constructing population-weighted Lorenz Curves for PB, CB, and DB-IAM accounts. Lorenz curves plot the cumulative attribution of global emissions (vertical axis) against the cumulative share of the global population (horizontal axis). The black line (y=1) denotes the line of perfect equality. At any point along this line, the global share of GHG attributions is equal to the global share of population. Deviations to the lower right of the line of equality demonstrate increasing inequality. For instance, at the midpoint of the line of equality, 50% of the world's population would be 'responsible for' 50% of the world's GHG emissions. However, the various accounting perspectives attribute only about 5-7% of global emissions to 50% of the global population.

Lorenz curves for the PB and CB perspectives describe the inequality in the global distribution of production versus consumption based emissions. The Lorenz curve for the DB-IAM reflects the inequality in the distribution of damages (wealth losses) due to global emissions, regardless of where they were released or where the resulting goods were consumed. Tightly nested Lorenz curves across PB, CB, and DB-IAM perspectives in Figure 7 indicate highly and similarly unequal global distribution of GHG attributions.

Figure 7. Inequality in emissions attributions: PB, CB, and DB-IAM accounting perspectives.

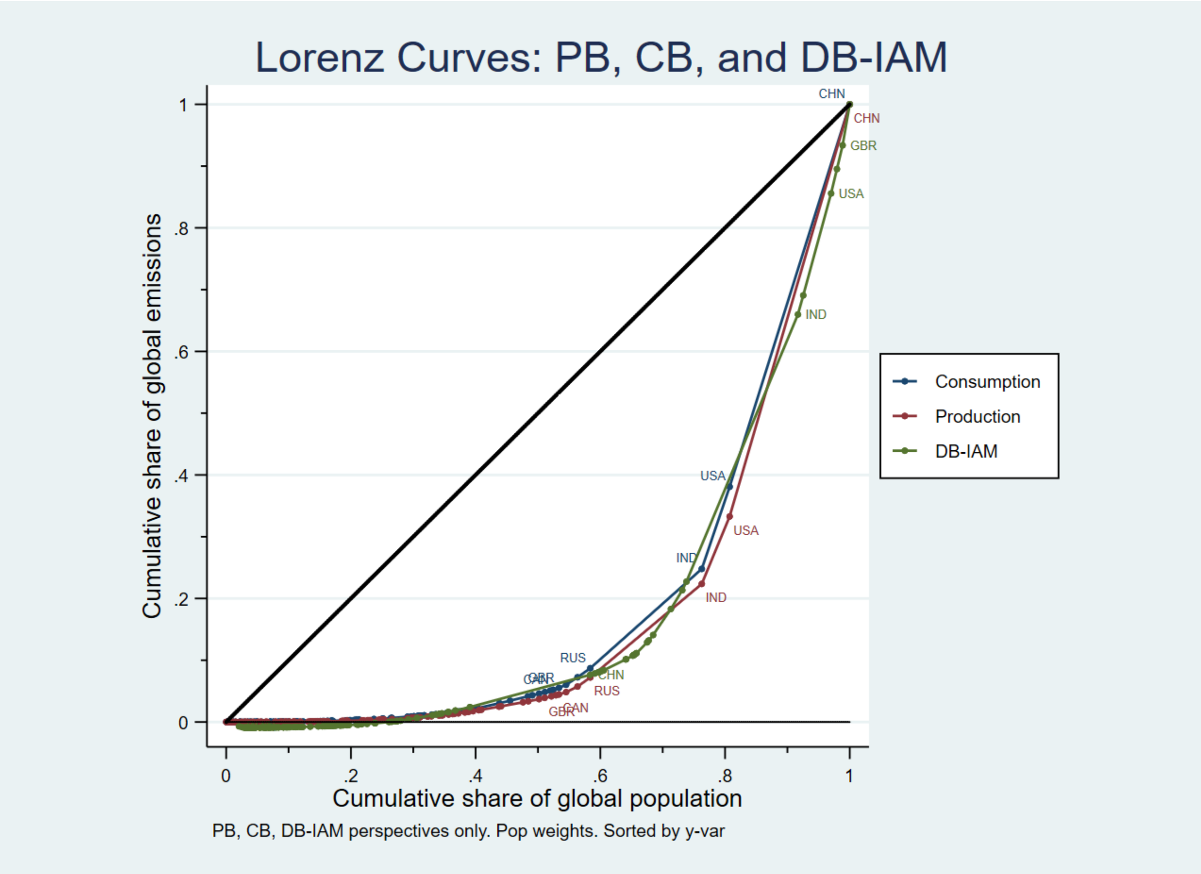

Figure 7. Population-weighted Lorenz Curves for PB, CB, and DB-IAM accounting perspectives suggest that each accounting perspective describes similar inequality in the distribution of GHG allocations. The black line indicates the line of perfect equality. Deviations to the lower right indicate rising inequality in the distribution. Attributions are highly and similarly unequal across each PB, CB, and DB-IAM perspectives: approximately half the world's population is accountable for just 5-7% of emissions attributions.

Comparing the full suite of accounting perspectives, Figure 8 shows that the DB-BHM perspectives yield the most unequal distribution of wealth depletion due to climate change. It is possible for Lorenz curves to drop below the horizontal axis. Here, negatively sloped Lorenz curves demonstrate shares of the global population that are expected to experience benefits from warming (as determined by each accounting perspective).

Within the three variants of the DB-BHM accounts, inequality decreases as the time horizon increases. This is because the initial marginal benefit of warming (negative damages) in currently cold countries are exhausted early-on. As climate changes, the negative consequences of additional warming moderate the distribution. However, Figure 8 clearly demonstrates that the DB-BHM perspectives indicate substantially more inequality arising due to GHG emissions than could be anticipated under PB, CB, or DB-IAM accounts. This is especially problematic because in the absence of international compensation for the wealth losses due to global emissions, this is the most reflective of the real world.

Figure 8. Inequality in emissions attributions: all perspectives.

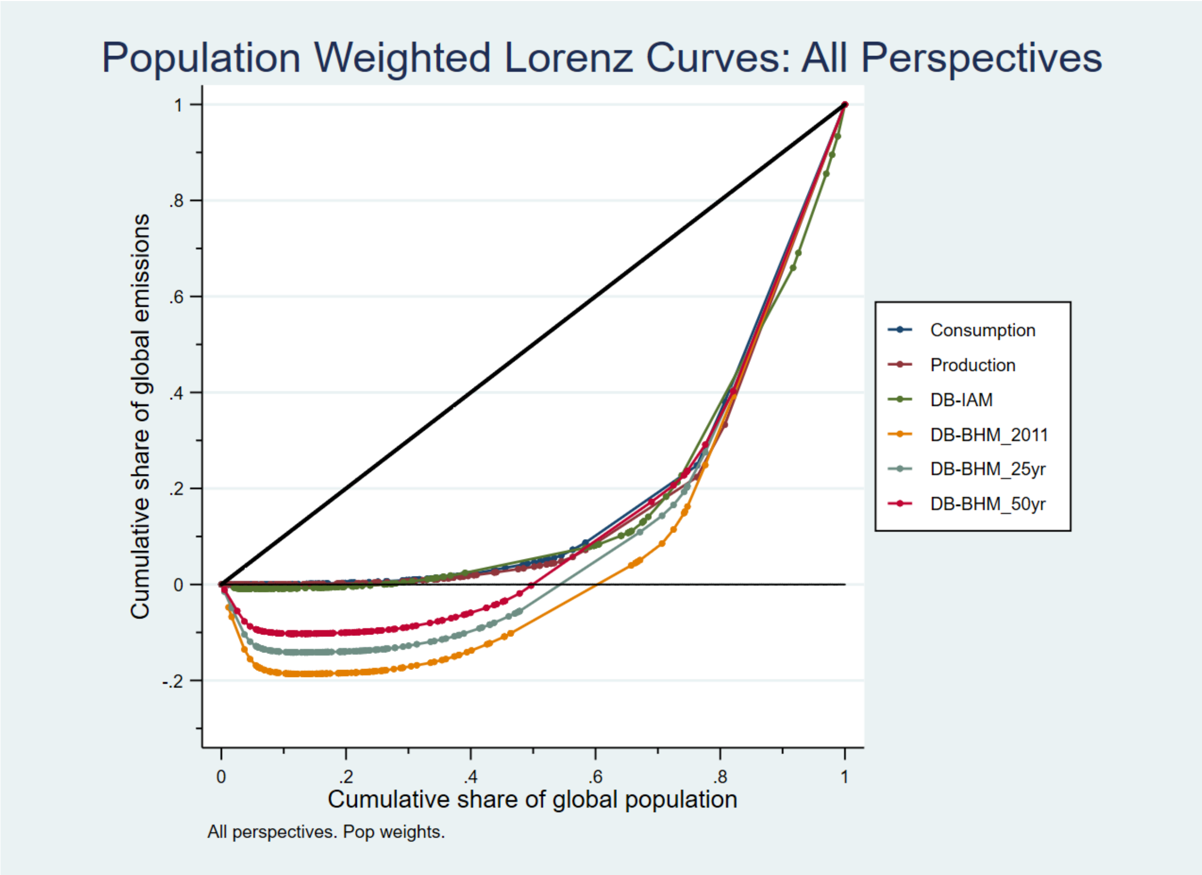

Figure 8. Lorenz curves illustrate inequality in emissions attributions across all accounting perspectives. DB-BHM_2011, DB-BHM_25yr, and DB-BHM_50yr refer to damage based coefficients calculated according to the 2011, 25-year, and 50-year slices of country-level climate impacts from Burke et al (2015), respectively. The black line indicates the line of perfect equality. Deviations to the lower right indicate rising inequality in the distribution.

6. Discussion & Policy Implications

GHG emissions represent a market failure that requires policy intervention. But in an increasingly globalized world, with goals in multiple domains of sustainable development, interventions must consider various interdependencies, vicious and virtuous feed-back loops, and complex trade-offs. Doing so requires a robust and reliable evidence base. Global climate change and the suite of Sustainable Development Goals represent multidimensional challenges. They are ill-served by unidimensional metrics. The argument here is not that one perspective should be adopted in lieu of the others, but that each offers useful insight into how progress towards sustainability might be measured. Sustainability science should provide the appropriate evidence bases to address multidimensional challenges from multiple angles.

GHG accounts are a useful starting point. Noting that countries can impact emissions at multiple points along the GHG supply chain (Davis et al; Steininger et al) an important literature has emerged exploring the implications of developing carbon accounts from various perspectives. But these have typically emphasized the location of emissions, and ignored the distribution of resulting damages. If the sustainability of nations is the goal, then wealth accounts reflecting the damages of climate change are the appropriate metric. Thus far, the carbon component of wealth accounts has typically relied on PB accounts. Not only is this the wrong evidence base for sustainability measurement, reliance on PB accounts systematically ignores the potential for countries to promote upstream and downstream decarbonization. Perhaps most importantly, failing to account for carbon damages overlooks what may be the greatest source of inequality within the SDG remit: the distribution of wealth depletions due to climate change. Our results have shown that for some countries, the difference can be substantial.

The research presented here could inform measurement and guide policy related to multiple SDGs. In particular, progress towards SDG 12 on responsible production and consumption will require at least PB and CB accounts to be constructed and monitored. These should reflect impacts along global supply chains, and incorporate additional elements of natural capital beyond carbon emissions. Similarly, SDG 8.4 aims to promote sustained, inclusive and sustainable economic growth by improving resource efficiency in production and consumption, decoupling growth from environmental degradation, and developing 10-year framework programs on sustainable production and consumption. To be meaningful, these framework programs should include PB and CB GHG accounts, and attempts to decouple growth and environmental impact need to account for upstream and downstream effects along global supply chains.

Our results also indicate that climate change could undermine progress towards reduced inequality (SDG 10) by more than was previously thought. The DB-BHM$_{2011}$ perspective uncovers the potential for much greater inequality in wealth depletions than is found in either PB or CB accounts. This is clearly evident in the variation in country-level damage coefficients illustrated in Fig 6, and the resulting Lorenz curves in Fig 8. That the SDG devoted to reducing inequality, and its suite of indicators, fails to mention inclusive wealth suggests that these inequalities could easily be overlooked.

Perhaps the most relevant SDG for this research is SDG 13: taking urgent action to combat climate change and its impacts. These goals provides the strongest justification for the development of damage based accounts. The impacts of climate change are not captured in PB or CB accounts. Only the DB perspective (whether using an IAM or country-level macroeconometric results as in BHM) actually complete the supply chain of GHG emissions by incorporating the incidence of the externality within an accounting framework. Moreover, the sustainability accounting story – linking the value of emissions to the wealth of nations according to their share of climate damages – also relates to ongoing policy discussions, particularly around how to disperse funds under the Green Climate Fund (SDG 13.a). One appropriate method could be to link the distribution of funds to shares of climate damages. This could identify those countries that should be 'first in line' for climate finance, and the actual release of funds could be tied to the merits of each individual project. That is, the Green Climate Fund could support a reverse auction in which funds available to any given country could be weighted by their share of climate-induced wealth depletions.

Finally, this research directly contributes to SDG 17.19: building on existing initiative to develop measurements of progress on sustainable development. Sustainability accounts constructed on the basis of any single accounting perspective will systematically ignore important lessons from climate science and undermine our understanding of the carbon wealth of nations. Climate change and the sustainability policies are too important to be exposed to the systematic blind-spots of any individual accounting perspective. A suite of accounts emphasizing different components of the carbon wealth of nations is necessary. The resulting evidence will be relevant to the design and evaluation of both climate and sustainability policies, and more importantly, to making them compatible with one another.

7. Conclusions

An important debate within the carbon accounting literature compares the ethical, policy and economic implications of accounting for the emissions generated within a country's borders (the territorial, or production perspective), versus adopting a consumption perspective that considers the (virtual carbon) emissions implicitly embodied within a country's final demand. We have contextualized this debate within the broader context of sustainability accounting and developed extended accounts to reflect the wealth impacts of the incidence of carbon externalities. Results indicate that different accounting perspectives yield substantively different understandings of country-level emissions and the contributions of individual nations to global (un)sustainability.

Carbon accounting has failed to reach its full potential in guiding sustainability science for several reasons. First, carbon accounts have not connected with the increasingly influential 'capitals theory' of sustainability, and its associated wealth accounting literature. This is because PB and CB accounts focus on the location of emissions, at the expense of the location of the wealth depletions. Moreover, the failure to address globalization and the rapid increase in international trade has undermined the potential impact of carbon accounts and national policies by failing to highlight opportunities for de-carbonization along global supply chains.

To address this we have developed multiple carbon accounts, made them theoretically consistent with the capitals approach to sustainability (by extending accounting procedures to include the incidence of climate damages, ie wealth depletions), and examined the distributional effects highlighted by each accounting perspective. Damage based accounts are constructed according to two scientific evidence bases, the RICE99 IAM and Burke et al (2015). Results are linked to multiple SDGs, and a dashboard approach comprising multiple accounting perspectives is advocated to help identify and overcome blind spots, and identify new areas to target effort and influence.

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