Natural capital accounting and the measurement of sustainability

Matthew Kane Agarwala

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Department of Geography and Environment,

London School of Economics and Political Science

Declaration

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ABSTRACT

This thesis contributes to the field of sustainable development by investigating complementary approaches to measuring the wealth of nations. The research adopts the ‘capitals theory’ of sustainability, which defines sustainability in terms of non-declining living standards and provides a clear wealth management rule: endowing future generations with the potential to be ‘at least as well off as the present’ requires that comprehensive wealth is non-declining over time.

Focusing on the natural capital component of comprehensive wealth, the thesis explores how individual countries might account for resource depletion against the backdrop of rising international trade, the presence of transborder externalities, and the development of international environmental policies. Recalling of Boulding’s notion of ‘Spaceship Earth’ the thesis investigates the implications of accounting for natural capital depletion within national borders (the production-based perspective) versus adopting a more global consumption-based perspective that attributes wealth depletions along a supply chain to the country of final consumption.

A 57-sector, 140-region multi-regional input-output model measures natural capital depletions from both the production and consumption perspectives, covering oil, coal, natural gas, minerals, ocean (fisheries), and forest (timber) natural capital depletions. The next paper expands the analysis to produce a new accounting perspective that incorporates carbon emissions as wealth depletions according to the damages they cause rather than the location of emissions. The discussion notes that each perspective entails policy ‘blind spots’ but that together they provide new insight into the measurement of national and global sustainability. The final paper links the thesis directly to global sustainability policy by investigating the extent to which measured progress towards the Sustainable Development Goals represents a genuinely new direction for the international development community.

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“We have to remember that what we observe is not nature itself,

but nature exposed to our method of questioning”

Werner Heisenberg

1. INTRODUCTION

21st century progress cannot be measured with 20th century statistics. We need a fundamental 'step-change' in accounting strategies. This simple observation has sparked global efforts to adjust, redefine, augment, complement, and even replace leading macro-economic statistics. A capacity for innovation and adaptation in national statistics is necessary. As economies evolve, so too must our tools of measurement. But there is now widespread recognition that established systems of national accounting and their associated macroeconomic statistics provide only a partial – and potentially misleading – view of modern economies (Wealth Economy 2019). Crucial omissions include issues of sustainability, human wellbeing, and inequality. In increasingly globalized, service-based economies, and against the backdrop of climate change, these blind spots could reduce the efficacy and relevance of official statistics. Put simply, the gap between national accounts and the world they seek to describe, is growing.

In *Physics and Philosophy,* Nobel prize winning physicist Werner Heisenberg notes that there is a "subjective element in the description of atomic events, since our measuring device has been constructed by the observer" (Heisenberg 1958). This thesis is motivated by a belief that the same is true of the description of economic events, because our measuring device – economic accounts – have been constructed by the observer. Accounting systems are tools for collecting, organizing, and reporting information that is useful for measuring trends and making decisions (Agarwala and Allan 2014; Coyle 2015; Obst et al. 2016; Agarwala and Brock 2018). The word 'useful' is key. Historically, the choice over what to include or exclude from the national accounts has been driven by political expedience rather than economic theory. Nor are national accounts necessary for economic growth (the UK's industrial revolution pre-dates the System of National Accounts by about half a century). Accounts are human constructs, strategically designed to help us measure trends and inform stories about the economy.

For much of the 20th century economic accounts were designed to tell stories of output, employment, and comparisons of growth in living standards over time and between countries. As these trends were measured, policies were designed specifically to boost the statistics. The growth imperative ushered in unprecedented improvements in the human condition (Rosling et al. 2018). But alongside these gains came over 1.5 trillion tonnes of CO_2 emissions, a global loss of biodiversity, and worldwide strain on ecosystems (Rockstrom et al. 2009; Steffen et al. 2015).

In threatening many of the welfare gains achieved over the past century, mounting environmental pressures provide a clear motivation for changing the economic story, moving beyond GDP, and placing sustainability at the centre of the economic model. The development of new economic statistics and systems of accounts is an important element of this transition and is the focus of this thesis. The unifying question I investigate is 'how can economic statistics help measure sustainability?' Inspired by Mead (1955), Boulding (1966), Asheim (1986), and Proops et al (1999), I pursue a 'cosmopolitan' view, devoting attention to questions of national versus global sustainability.

Amid many competing definitions of sustainability, I adopt what may be called the wealth theory of sustainability. The theory emerges from the notion that future consumption depends on future productive capacity, which in turn depends on current net investment in capital (Hartwick 1977; Dasgupta and Heal 1979; Solow 1986; Asheim 2000; Dasgupta 2001). 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 off as the present' requires that comprehensive wealth is non-declining over time. Following initial empirical contributions by Pearce and Atkinson (1993a), wealth accounting research seeks to measure the extent to which individual countries adhere to the sustainable capital management rule (Pearce and Atkinson 1993a; World Bank 2006, 2011; UNU-IHDP and UNEP 2012, 2014; Atkinson et al. 2014; Hamilton and Hepburn 2017; Fenichel et al. 2018; Lange et al. 2018; Managi and Kumar 2018).

I investigate accounting methods for the natural capital component of comprehensive wealth. The term 'natural capital' provides both a powerful metaphor and an organizing intellectual framework for viewing nature through the economists' lens. To some, it is a contemptible premise. Nature is not for commoditization. For others, 'nature as capital' opens opportunities to bring the tools of economics to the challenge of conservation. The chief motivation for thinking in terms of natural *capital* rather than 'the environment' is to apply our understanding of capital theory, capital valuation, management of net investments, and the utilization of capital services to generate human wellbeing (Binner et al. 2017). For this reason, natural capital refers to stocks of environmental assets that benefit people by generating flows of welfare-enhancing environmental goods and services. Stocks include fish in oceans and rivers, standing timber, mineral and fossil fuel deposits, and a stable climate. Some applications take a portfolio approach, noting that ecosystems are natural capital assets that contain and combine multiple individual forms of capital (water, standing timber, biodiversity).

An important debate within the wealth theory of sustainability examines the extent to which the various capitals may be substitutable for one another. Early theoretical contributions (Solow 1974a, b; Hartwick 1977, 1978) emphasised the importance of the overall value of the comprehensive capital stock, but remained agnostic about its specific composition. Loosely, the theory permitted the existence of sustainable development paths along which natural capital was continually depleted (including the point of exhaustion), so long as sufficient investments were made in alternative forms of capital. This substitution variant of the wealth theory became known as ‘Weak Sustainability’ (Neumayer 2014). In contrast, an opposing paradigm argues that natural capital deserves special treatment within the wealth theory on the grounds that it provides critical life support functions and is therefore limited in its substitutability with other forms of capital. This ‘Strong Sustainability’ paradigm itself has two variants, one calling for the overall value of natural capital to be maintained (but permitting substitution between types of natural capital), and another which identifies critical thresholds of specific natural capital stocks which must be maintained to preserve functioning global life support systems.

Which paradigm best describes reality is a question that (i) may be unanswerable because neither paradigm is falsifiable (Neumayer 2014) and (ii) I choose to remain agnostic about. Early contributions to the wealth theory largely focussed on non-renewable natural capital, where the flow from the depleting stock was an input into production. The sustainability question is therefore only relevant if sufficient substitutability is assumed. The important subsequent question is whether such substitutability applied to all elements of natural capital. This question remains unresolved. However, one simple observation will be made: reconciling weak and strong sustainability will require both theoretical and empirical contributions. In focusing on the design of natural capital accounts, this thesis may ultimately contribute to the latter. Moreover, whichever paradigm one adopts, natural capital accounts will be necessary to measure net investment for each asset class. The decision to focus on natural capital is motivated by its role in the global economy, its current treatment in economic statistics, and multiple unique characteristics which combine to make it an interesting topic for economic research. Natural capital provides the raw materials of which physical capital is comprised, the life support systems which enable humans to deploy all other capitals in the generation of welfare, and the operating space in which to do it. That is, natural capital underpins all wealth and welfare in the economy. Despite this, it has been poorly reflected in mainstream macroeconomic statistics.

Continuous natural capital depletion is behind myriad looming environmental challenges, from climate change and species loss to air pollution, ocean acidification, and desertification. These mounting environmental pressures threaten to undermine economic welfare. The need for deliberate natural capital management has prompted new interest in natural capital accounting measures from the World Bank, United Nations, and by individual national statistical offices. That these standards are still in development is a key reason for the present focus on natural capital. Further motivation comes from a series of landmark global studies which, using different methods and approaches, converge towards the same conclusion: natural capital is the only component of wealth that is facing sustained, global decline (Millennium Ecosystem Assessment 2005; Lange et al. 2018; Managi and Kumar 2018).

Finally, natural capital exhibits unique and challenging characteristics that make it an exciting area for economic research. It exists and is managed under all permutations of property rights regimes, variously exhibiting characteristics of pure- and quasi- public and private goods. Crucially for the research set out in chapters 2 and 3, it transcends political and economic boundaries, both in terms of managing transboundary stocks and addressing externalities. The combination of complex property rights and transboundary impacts and dependencies forces economists to incorporate lessons from natural science and political economy, and provides an opportunity to re-imagine economic statistics for a globalised world. The prevalence of tipping points, non-linearities, and irreversibilities in stock dynamics further differentiate natural from other types of capital. Whereas physical infrastructure can be destroyed and rebuilt, the extinction of species cannot be undone. An important and poorly understood feature of natural capital is its substitutability with other elements of wealth. This too, suggests natural capital deserves special attention.

Focusing on natural capital within the wealth theory enables me to explore conceptual nuances in the way we might construct accounts. A core theme of the first two papers explores how arbitrary decisions around accounting boundaries, domestic versus global natural capital management, and the treatment of international trade might shape the kind of information that accounts can convey.

Most natural capital and comprehensive wealth accounting initiatives employ a territorial, or production-based accounting perspective. That is, they include natural capital stocks that lie within a country's borders and exclude foreign natural capital. This is a choice rather than a scientific or economic necessity. In his seminal treatise on trade and welfare, James Meade (1955) noted that "in applying the criteria of economic welfare to the problems of international economic policy, it is possible to take either a national or a cosmopolitan view" (Meade 1955, p9), where the cosmopolitan view referred to the global economy. A chief contribution of this thesis is to consider how natural capital accounts might differ if the territorial boundaries were relaxed.

The need to incorporate international trade arises from two simple observations. First, fossil fuel markets are highly globalized: nearly 40% (5,181.03 Mtoe) of the total primary energy supply in 2012 (13,371 Mtoe) was traded across national borders (International Energy Agengy 2014). Second, the shares of both carbon and natural resources embodied within internationally traded goods and services are substantial and growing (Davis et al. 2011; Peters et al. 2011; Sato 2013). It is therefore increasingly clear that no policy or accounting system is complete without considering the international dimension. Accounting systems that clearly reflect the trade dimension of sustainability can enrich policy development and evaluation.

The focus on natural capital component and the wealth theory of sustainability in no way undermines the importance of high quality accounting for social, physical, institutional, and human capitals, which are integral to the theory. Nor does this choice negate, refute, or belittle the important contributions from competing and complementary theories of sustainability from disciplines such as anthropology, sociology, political science, and ecology. Rather, the intention is to demonstrate that economic measurements informed by economic theory can usefully add to the stock of knowledge on sustainable development. The knowledge gaps I address entail three crucial omissions from mainstream economic statistics: the loss of natural capital, the transboundary nature of environmental impacts and dependencies, and extent to which global sustainability policy (namely the Sustainable Development Goals) represent a genuine departure from business as usual. My chief contributions are of an empirical and policy-oriented nature. I propose a natural capital dashboard comprised of a suite of accounts, each deliberately designed to elucidate a specific relationship between national economies and global environmental-economic impacts. It would include natural capital accounts constructed from the production and consumption perspectives, in totals and on a per capita basis, as well as the country's exposure to climate risk. In combination, the dashboard would provide a more complete accounting for natural capital impacts and dependencies, and facilitate greater scrutiny over the real-world efficacy of sustainability policies.

Inspired by the wealth theory of sustainability, the accounting perspectives developed in Chapters 2 and 3 provide new ways of looking at the world, its depletions of natural capital, and the role of individual countries in environmental change. Chapters 2 and 3 respond to a knowledge gap highlighted by the Sarkozy Commission which noted that a measurement approach "centred on national sustainabilities may be relevant for some dimensions of sustainability, but not for others" (Stiglitz et al. 2009b, p77). Chapter 2 extends a debate over production versus consumption based accounting beyond greenhouse gas emissions to incorporate six additional components of natural capital: oil, coal, gas, minerals and rare earth metals, timber, and fishery resources. Chapter 3 places greenhouse gas accounting on a stronger footing within the wealth theory of sustainability by attributing emissions (that is, wealth depletions) to the countries according to the welfare losses they might incur, rather than their domestic emissions.

My results demonstrate that arbitrary accounting assumptions have substantial implications for the types of information that accounts might convey. Focussing on domestic natural capital depletions ignores global footprints, resource dependencies, and transboundary externalities. In such accounts, improved domestic natural capital management may mask greater environmental pressures elsewhere: an offshoring or leakage effect. Consumption-based accounts can help to highlight these international dimensions of natural capital management. The different accounting perspectives developed in Chapters 2 and 3 provide completely different maps of the world. Relying on any one of these perspectives to the exclusion of others imposes evidence and policy blind spots. The resulting suite of accounts enables us to analyse natural capital depletions from multiple angles, leading to a more comprehensive understanding of sustainability in an increasingly globalised world.

The final paper steps outside the wealth theory of sustainability. In doing so it represents a substantial conceptual departure from the rest of the thesis. But in terms of its focus and contribution, it is entirely in keeping with my overarching question of what economic statistics can tell us about sustainability. The wealth theory that informs Chapters 2 and 3 is just one of many potential frameworks in which to investigate sustainability. Those chapters explore what new types of accounts might be useful. Chapter 4 adopts a different framework for defining and measuring sustainability, and addresses a different set of challenges therein. The framework is provided by the 17 Sustainable Development Goals (SDGs) adopted by the United Nations in 2015. In combination, they effectively 'reveal' the global community's view of what sustainability entails. However, a common critique of sustainability metrics and indeed all 'alternatives to GDP' is that they either (i) correlate so closely with per capita GDP that they add very little new information, or (ii) correlate so poorly with per capita GDP that they ignore very important information. A parallel question posed by Thomas Schelling (1992) concerns whether poor countries should sacrifice growth to reduce climate change, or whether they should develop at all costs and face the environmental consequences later, as richer economies. Chapter 4 examines data on SDG performance in an attempt to shed light on both of these questions: does SDG performance genuinely go 'beyond GDP' and, if SDG performance is the globally agreed definition of sustainable development, should countries attempt to achieve it by a narrow focus on per capita GDP growth or should they pursue broader environmental and social objectives as well?

The first two papers of this thesis address the domestic and global nature of the natural capital impacts of nations. Incorporating international trade in natural resource explicitly, the first paper constructs and contrasts natural capital accounts from the production and consumption perspectives. The second paper focuses on the treatment of greenhouse gas emissions within wealth accounts, and asks where along the global supply chain might we attribute the natural capital depletions generated by emissions. Finally, the third paper returns to the broader question of economic measurement for a sustainable 21st century. Here, I examine the extent to which the 17 Sustainable Development Goals represent a genuine departure from 'development as normal'. In combination, the research offers insights into the difference between national and global sustainability, and how we might measure the sustainability of development. Each paper includes its own introduction and conclusion, and comments on the policy relevance of the work. The final section of the thesis reflects on lessons learned and potential next steps.

2. PRODUCTION AND CONSUMPTION ACCOUNTS FOR NATURAL CAPITAL DEPLETIONS

In the post-war era globalisation has opened markets, facilitated the spread of people, ideas and culture, and lifted millions out of poverty. But it has also ushered in an era of unprecedented natural resource depletion and environmental change. Many of the development challenges we currently face deal with the intersection of these two trends: the benefits of economic activity and the costs of environmental degradation. International trade plays an important role in both (Dupuy 2011; Dupuy and Agarwala 2014). It separates the location of production from that of consumption and drives a wedge between those who demand natural resources, the countries that govern them, and those who experience the associated social, economic, and environmental consequences. Measurement systems that fail to account for this offshoring effect may provide a distorted picture of national and global sustainability.

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 (Weitzman 1976; Dasgupta and Heal 1979; Dasgupta 2001; Arrow et al. 2012). 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 off as the present' requires that comprehensive wealth is non-declining over time. Following initial empirical contributions by Pearce and Atkinson (1993a), wealth accounting research seeks to measure the extent to which individual countries adhere to the sustainable capital management rule (Atkinson et al. 2014; Hamilton and Hepburn 2017).

Most wealth accounting efforts employ territorial accounts that describe trends in natural capital stocks within a country's national borders and are therefore relevant for calculating domestic per capita natural capital depletions. Trade enters solely through the effect of net exports on national savings. We argue that because international trade is a large and growing share of the global economy, rising from just 24% of gross world product in 1961 to 64% in 2011 (World Bank 2018), there is justification for re-examining the extent to which territorial natural capital accounts are fit for purpose when measuring national and global sustainability in an increasingly globalised world. Indeed, the influential Sarkozy Commission noted that a measurement approach "centred on national sustainabilities may be relevant for some dimensions of sustainability, but not for others" (Stiglitz et al. 2009b, p77).

Entering into force in 2016, the Sustainable Development Goals address multiple development challenges, ranging from ending poverty and hunger to addressing climate change and developing institutions and partnerships. A key strength is that they explicitly recognise the role that globalisation plays in driving and addressing social, economic, and environmental challenges of sustainable development. Several of the goals and indicators deal directly with natural resource flows and material footprints. This paper focuses on developing the evidence base for measuring progress towards SDG 12, to "ensure sustainable production and consumption patterns" (Sachs et al. 2019). The goal rightly recognises the diverging natural capital footprints of resources used in production versus consumption activities, and marks the need for accounting mechanisms that can measure not just the domestic, but also the global nature of sustainability.

We propose the development of two simultaneous and complementary natural capital accounts, one from the traditional production, or territorial based perspective, and another from the consumption-based perspective. Production-based accounts record resource depletions that take place within a country's borders over the course of a year, regardless of where those resources are ultimately consumed. Consumption based accounts record resource depletions embodied within a country's final demand, regardless of where in the world those depletions actually took place. Examining both sets of accounts simultaneously provides a more complete understanding of an economy's contributions towards both national and global sustainability, provide insight into dependencies on domestic versus global resource stocks, are crucial to understanding resource security concerns, and may identify opportunities for joined-up bilateral and international resource policy. To show that both accounts convey different information about the natural capital depletion of nations, we develop a 57-sector, 140-region multi-regional input-output model and examine natural capital depletions covering six natural resources: oil, coal, natural gas, minerals, fisheries, and timber.

The chief contribution of this chapter is to extend the discussion of production and consumption accounting that exists around greenhouse gases (Davis et al. 2011; Steininger et al. 2016; Afionis et al. 2017) to incorporate other elements of natural capital. This provides countries with a more complete understanding of their natural capital impacts and dependencies, and helps reduce 'policy blind spots'. By measuring both domestic and international trends in emissions, countries can assess leakage effects and potentially identify opportunities to improve natural capital management via treaties, trade deals, and technology transfers with key trade partners. The breadth of resources considered here is an important extension: oil, coal, gas, minerals, fisheries, and timber have all been the focus of resource security concerns in rich and developing countries.

2.1.The wealth theory of sustainability

In an early effort to embed sustainability within official statistics, Nordhaus and Tobin (1972) made three core adjustments to gross national product. They distinguished between intermediate and final output, shifted the focus from production to consumption, and developed a preliminary measure of ‘net investment’. The focus on consumption rather than output was thought to place greater emphasis on welfare – indeed the authors claim that “the goal of economic activity, after all, is consumption” (1972, p4). Perhaps the more important contribution was the idea that measures of sustainable economic welfare must make adjustments for the depletion of capital (net investment). That nature provides a suite of capital assets that are necessary for economic production has a long history in economics. Indeed Irving Fisher included mining land, fisheries, timber land, and mineral materials as components of wealth as early as 1906 (Fisher 1906). What Nordhaus and Tobin (1972) argued was that any measure of sustainability would need to directly account for changes in capital.

The establishment of the Sustainable Development Goals is a clear acknowledgement that economic progress is not adequately measured by standard official statistics such as gross domestic product (GDP). Leading economists have supported calls to move ‘beyond GDP’ for at least half a century (Coyle 2015). Arguments for doing so can largely be grouped into three broad categories. First, established macroeconomic statistics fail to adequately reflect changes in human wellbeing and in the worst instances can lead decision-makers to pursue welfare reducing policies (see the various works of Amartya Sen, capably reviewed in Hamilton (2019), but also Easterlin (1974; 2010) and Layard (2011). Second, by focusing on income flows rather than capital stocks, official statistics such as GDP omit considerations of sustainability, providing a potentially misleading view of the long-run viability of an economy. Third, although the standards and guidelines governing the calculation of official statistics are constantly under review, they have failed to keep pace with the changing nature and structure of economic activity. There is growing concern that international trade and transboundary externalities are (i) increasingly important factors in the global economy and (ii) poorly reflected in official statistics. This paper focuses on the intersection of the latter two issues: sustainability and international trade.

Amid multiple competing definitions and interpretations of what ‘sustainability’ may mean, the Brundtland Commission’s view that development is sustainable if it “meets the needs of the present without compromising the ability of future generation to meet their own needs” (Brundtland et al. 1987, p41) stands out. It can be adopted and adapted by countries in all stages of development, is applicable across multiple academic disciplines, and can be linked to clear policy objectives. Solow (1994) simplifies the definition, noting that “a sustainable path for the *national* economy is one that allows every future generation the option of being as well off as its predecessors" (emphasis added, Solow (1994, p25). This interpretation links the spirit of Brundtland to the theory of economics and the practice of sustainability measurement. An established theoretical result in resource economics is that because future welfare depends on future productive capacity, sustainability requires that an economy's broadly defined productive capacity is non-declining over time (Dasgupta 2001; Atkinson et al. 2014). Here, productive capacity includes all forms of capital – produced, human, natural, social, and intangible – that can be used to generate human welfare. Let us call this inclusive wealth.

Solow (1974a) showed that if the elasticity of substitution between exhaustible natural resources and alternative forms of capital was greater than unity, constant consumption could be maintained even if production entailed the use of finite non-renewables. Hartwick (1977) showed that this implies a strict savings rule: the competitive rents from non-renewable resources must be reinvested in alternative forms of capital. Several extensions quickly followed. Hartwick (1978) extended the analysis to include both renewable and non-renewable resources, Dixit et al (1980) generalize the result, and Dasgupta and Heal (1979) and show that the Hartwick Rule requires an elasticity of substitution between natural and man-made capital of at least 1. Solow (1986) offers a Hartwick-inspired 'rule of thumb', namely that the sustainable consumption level would be just equal to the annual interest generated by an economy's inclusive wealth.

Combined, these contributions form the basis of the wealth theory of sustainability. Its principle tenets are (i) that multiple forms of capital make up the productive base, or inclusive wealth of an economy and (ii) sustainability requires that the value of this broadly defined inclusive wealth is non-declining over time. Given (iii) that substitution is possible between types of capital, the use of non-renewable natural capital is still possible along a sustainable development path, so long as (iv) a Hartwick Rule is followed. Noting that (v) it is the net change in wealth over time rather than its level that determines whether a path is sustainable, Pearce and Atkinson (1993a) developed a simple savings rule to assess the extent to which national economies were maintaining inclusive wealth, and were the first to present empirical estimates for a range of countries. Hamilton and Clemens (1999) formalised the savings rule for an optimal economy, Dasgupta and Maler (2000) extended to the non-optimal economy, and the World Bank developed wealth accounts and calculated Genuine Savings dating back to 1970 (Lange et al. 2018).

2.2. The wealth theory of sustainability and international trade

The development of wealth accounts and the genuine savings measure as an indicator of weak sustainability represents a significant advancement in the economics of sustainability. However, in focusing on illustrating the links between natural resources, wealth, savings and depletions, the various contributions outlined above made a series of theoretical simplifications: closed economies, constant population, and stationary technology. The closed economy assumption is increasingly irksome given the growth of international trade in natural resources (Dupuy and Agarwala 2014). Trade drives a wedge between domestic and international resource depletions, and the presence of transboundary externalities (and therefore imperfect markets for natural capital resources) means that merely relying on import prices in adjusted savings metrics would systematically bias any individual country's measured progress towards national versus global sustainability (Oleson 2011; Atkinson et al. 2012; Wiedmann et al. 2015; Steininger et al. 2016). Of course, if natural capital resources embodied in international trade were priced at their theoretical shadow price, this would not be an issue because genuine savings measures account for net exports. But when natural capital is traded below its shadow price, this adjustment fails. If natural resources are exchanged on international markets at prices that deviate from their optimum shadow price, then international trade implicitly entails transfers of 'virtual sustainability' between resource exporters and importers. The more natural capital is traded internationally, the more important this distortion becomes. UNEP (2015) show that in physical terms, resource extraction increased by a factor of 1.8 from 1980 to 2011, but that resource trade increased by a factor of 2.5, meaning the divergence between domestic and global resource use is accelerating.

In his seminal treatise on trade and welfare, James Meade (1955) noted that "in applying the criteria of economic welfare to the problems of international economic policy, it is possible to take either a national or a cosmopolitan view" (1955, p9), where the cosmopolitan view referred to the global economy. The intuition behind this dichotomy was applied more directly to environmental issues in Boulding's (1966) essay, "The economics of the coming spaceship Earth". Boulding caricatured two economies. The 'cowboy economy' was open, "symbolic of the illimitable plains and also associated with reckless, exploitative, romantic and violent behaviour, which is characteristic of open societies," whereas the 'spaceman economy' imagines Earth as "a single spaceship, without unlimited reservoirs of anything, either for extraction or for pollution, and in which, therefore, man must find his place in a cyclical ecological system…" (Boulding 1966, p4). One interpretation of Boulding's message is that in a world of abundance, individual economies can behave like cowboys. But as population and affluence grows, that illimitable and relatively open system will approach planetary boundaries and Earth must instead adopt the spaceman economy. It is important that in Boulding's spaceman economy the primary measure of success is the extent, quality, and maintenance of the capital stock.

Boulding's intuition that the capital stock (ie inclusive wealth) is the object of interest was clearly supported by the earliest papers on wealth theory of sustainability. But the question of international trade, open and closed economies, and cowboys and spacemen took longer. It wasn't until 20 years after Boulding's essay, and nearly 10 years after the first appearance of the Hartwick Rule, that the savings rule was extended to the open economy setting. A crucial result was that the strict Hartwick Rule described in the previous section need not hold in the open economy setting. Asheim (1986) showed that in a general equilibrium setting an open economy could violate the Hartwick Rule if (i) it is a net exporter and (ii) the resource rent is rising over time in line with the Hotelling Rule (Asheim 1986). He notes that "in a world economy adhering to a maximin criterion, it is the resource-consuming economies' – not the resource-producing economies' – responsibility to transform a declining resource base into reproducible capital" (Asheim 1986, p400). Asheim stops short of saying exporters could be cowboys while importers must be spacemen, but the importance of international trade for the wealth theory of sustainability had been demonstrated. More recently Arrow et al (2012) show that in the presence of transboundary negative externalities such as climate change, the appropriate reduction in genuine savings includes the domestic damages generated by global emissions rather than the emissions generated domestically.

These are not merely theoretical nuance. They have direct implications for sustainability measurement in an increasingly globalised world and concerns over global (rather than national) natural capital depletions feature prominently in policy debates. The need to incorporate international trade arises from two simple observations. First, fossil fuel markets are highly globalized: nearly 40% (5,181.03 Mtoe) of the total primary energy supply in 2012 (13,371 Mtoe) was traded across national borders (International Energy Agengy 2014). Second, the shares of both carbon and natural resources embodied within internationally traded goods and services are substantial and growing (WTO 2010; Fischer 2011; Peters et al. 2011; Sato 2013; Wiedmann and Lenzen 2018). It is therefore increasingly clear that no policy or accounting system is complete without considering the international dimension. Accounting systems that clearly reflect the trade dimension of sustainability can enrich policy development and evaluation. For instance, Atkinson et al (Atkinson et al. 2011) explore how border taxes might be designed to 'level the playing field' in the face of unequal emissions caps. Peters et al (2008; 2011) showed that from 1990-2008, increased virtual carbon imports by developed countries exceeded their combined emissions reductions under the Kyoto Protocol (carbon leakage).

2.3. Production and consumption accounting

We develop a 57 sector, 129 region input output (IO) model to explore how two distinct accounting perspectives – production (aka territorial) and consumption – might inform climate and resource policy discussions within the context of international trade (Leontief 1936; Miller and Blair 2009). The notions of production and consumption accounting may be familiar from a rapidly growing literature on carbon accounting (Atkinson et al. 2011; Peters et al. 2011, 2012; Sato 2013; Raupach et al. 2014; Afionis et al. 2017; Lenzen et al. 2018). We contribute to this literature by expanding the analysis to incorporate additional elements of natural capital depletion. By including a broader set of natural capital assets (fossil fuels, fisheries, forestry and mineral extraction) our analysis permits a broader understanding of 'sustainability accounting'.

The MRIO enables us to construct natural capital accounts from both the production and consumption-based perspectives. This is a useful exercise for several reasons. First, mainstream economic statistics conceptualise economies as isolated national entities connected to the 'rest of the world' only through net exports. But this simplistic view of the role of international trade in modern economies conceals important relationships and trends in resource dependence and environmental impacts. This is important for policy because countries may be able to exert influence on resource management beyond their borders through trade relationships, treaties, and international policies such as the Paris Agreement and the Sustainable Development Goals. Second, the wealth theory of sustainability demonstrates that non-declining wealth over time is a prerequisite for sustainability. But international trade in natural resources drives a wedge between resource production and consumption. Does trade offer countries the opportunity to 'import (virtual) sustainability'? This is directly related to a third motivation, namely that the combination of production and consumption accounts provides a more detailed evidence base for informing the political economy of international resource dependence. Combined, these accounts might shed light on new opportunities to develop international resource policy.

An increasingly influential carbon accounting literature stresses the importance of developing both production and consumption based accounts for greenhouse gas emissions (Steininger et al. 2016; Afionis et al. 2017). An important debate within this 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 (Peters and Hertwich 2008).

Atkinson et al. (2012) extend the analysis beyond GHGs alone to consider a broader set of environmental resources, thus linking the production versus consumption debate to comprehensive wealth accounting. Examining a suite of natural capital assets embodied in international trade reveals important insights for understanding broader trends in resource use. In particular, Atkinson et al. (2012) show that for many countries there is a substantial difference between the value of natural capital depletions used to produce total output (the territorial perspective) and that necessary to satisfy its final demand (the consumption perspective). They find that for low and middle income countries, territorial natural resource depletions exceed consumption based depletions, but that for high income countries the relationship is reversed: the value of consumption based depletions exceeds that of territorial depletions by approximately double.

Building on Atkinson et al (2012) we place the production and consumption accounting debate within the context of SDG 12. Results indicate that adopting the territorial versus consumption-based perspective leads to statistically significant impacts on carbon, natural capital and comprehensive wealth accounts. The accounts we develop enable an applied and empirical discussion of wealth accounting in a globalised world, and are necessary for measuring progress towards SDG 12.

An important caveat is that, consumption accounting, either of carbon or more broadly defined natural capital, introduces its own set of challenges and shortcomings. Data for generating territorial inventories require inputs from fewer statistical organizations, fewer manipulations and less aggregation than for consumption-based inventories (which require MRIO analyses) (Peters and Hertwich 2008). Furthermore, whereas territorial accounts represent one extreme in which consumers hold no responsibility for emissions and natural capital depletions, consumption accounts represent another extreme in which producers hold no responsibility. It is not clear that one is better than the other: producers and consumers both share the gains from trade. Thus, a reasonable compromise might be to develop a method of sharing responsibility for emissions and depletions between producers and consumers (Lenzen et al. 2007; Raupach et al. 2014; Afionis et al. 2017). This warrants further study, as the shared responsibility mechanisms developed for carbon emissions focus on combining trends in historical emissions with equity goals for per capita emissions (Raupach et al. 2014) and may not be readily applicable to other elements of natural capital. For sustainability accountants, the interest in broader natural capital might suggest that responsibility for emissions and depletions could be allocated in proportion to value added, as in Lenzen et al. (2007).

Further challenges and caveats relate to issues of national sovereignty and the responsibility for foreign natural resource management. Why should importers concern themselves with the internal affairs of exporters? One argument for focusing on domestic production accounts is that this is the only area over which governments have the legitimacy to govern: countries should not infringe upon the sovereignty of others by attempting to exert influence beyond their borders. Whilst it is certainly true that the international political economy of resource use can be contentious, a narrow inward-looking evidence base predicated on territorial accounts limits the information available to policy makers. Moroever, the scale of diplomatic representations around the world – the Global Diplomacy Index covers just 61 countries with a combined 7,320 international diplomatic posts – suggests that countries do exert influence beyond their borders (Lowy Institute 2019). However, even if we ignored this and pretended countries were only concerned with domestic governance, it would still be of interest to understand issues of leakage and resource security. More importantly, in the presence of transboundary externalities, national sovereignty is already violated. This is particularly important in the management of natural resources, for instance international fisheries, transboundary rivers, air pollution, and climate change. An important literature in economics explores how agents might collaborate and coordinate to govern the global commons. The accounts developed here help to ensure that these processes can incorporate the most comprehensive evidence base possible. Finally, there is some precedent for considering negative externalities of imports on moral grounds. The avoidance of child, sweatshop, and slave labour; prohibitions on blood diamonds; and certifications of fair trade products all demonstrate a desire understand the provenance of internationally traded goods and services.

A more problematic challenge is that the data described below does not adjust for sustainably versus unsustainably managed resources. Harvesting timber from a sustainably managed plantation is clearly different from illegal logging of irreplaceable primary rainforest. Similarly, virtual carbon imported from industries regulated by the EU ETS do not represent increased emissions in the same way that unregulated virtual emissions would. Ideally, a distinction would be made between sustainably managed resource consumption and unsustainable natural capital depletion. With sufficient data, future IO models could incorporate a 'sustainability matrix' to adjust for resource management practices. That the data do not allow this distinction to be made is an important caveat, but it is hoped that the results may still be useful in providing a broad overview of the resource depletions of nations. However, in aggregate the renewable resources considered here (fisheries and forestry) are in global decline.

The argument here is not that one perspective should be used in lieu of the other, but rather that each offers useful insight into how progress towards sustainability might be measured and should be considered when developing, implementing and evaluating policy. At a fundamental level, accounts are simply tools for measuring change over time. The story they tell depends on how they are designed.

2.4. Data and Methods

Data for this analysis come from the Global Trade Analysis Project's (GTAP) version 9 database, which covers 57 sectors across 140 countries and regions for the year 2011 (Narayanan et al. 2015). Although it was developed to support computable general equilibrium modelling, GTAP's global IO database has been used in numerous carbon accounting studies (Proops et al. 1999; Davis and Caldeira 2010; Davis et al. 2011; Atkinson et al. 2011, 2012). Two chief advantages of GTAP are that it is already balanced (for analysis at different scales of analysis) and that sectoral disaggregation is harmonized across regions. Data on natural capital depletion values (resource rents) for oil, gas, coal, fisheries, forestry, and mining for 2011 are from GTAPv9. 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 the bilateral trade in energy products. Emissions data contained within GTAPv9 covers 28,818 million tonnes of CO_2e emissions from fuel combustion and major non-CO_2 GHGs (CH4, N20, CF4, HFCs and SF6) 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 (Rose et al. 2010) to which an emissions growth function is applied as in Ahmed et al. (2014). The MRIO model is described in Appendix 1.

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.

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 and Botzen 2014; Nordhaus 2017; Ricke et al. 2018) a globally agreed value for carbon emissions remains elusive. Nordhaus (2017) uses DICE to calculated a SCC of \$31/tCO_2. 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. 2014a). 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.

Two important caveats deserve consideration before the results are discussed in detail. First, the data considered here does not adjust for the re-growth of renewable resources, so they are implicitly treated as non-renewables in their interpretation. Strict adherence to the wealth theory would require that analysis takes place in 'net' terms, which would incorporate new discoveries of non-renewables and the natural (net) regeneration of fish and forest stocks. The inability to make these adjustments here is an important caveat. However, widespread overfishing could turn previously renewable stocks into non-renewables if fisheries are unable to recover. There is some evidence for this. The World Bank's authoritative report on the state of the world's fisheries found that "the proportion of fisheries that are fully fished, overfished, depleted, or recovering from overfishing increase from just over 60 percent in the mid-1970s to about 75 percent in 2005 and to almost 90 percent in 2013" (World Bank 2017, p. 1).

The more important caveat is that the wealth theory requires changes in net wealth to be valued at the appropriate shadow price, which would fully reflect the marginal contribution to intertemporal welfare created by a change in the quantity of the stock. In practice, these theoretical shadow prices are impossible to observe and the standard approach in the literature is to compute resource rents as a crude approximation. This is a fundamental and as yet unresolved challenge in the wealth accounting literature and the results discussed below are open to criticism on this front.

Natural capital resource depletions contained in the GTAPv9 database for the year 2011 summed to just over one trillion US dollars, excluding greenhouse gas emissions. Of this, fossil fuels (USD 837.3 billion) comprised the largest share, with \$639 billion from oil and with coal and gas relatively equal at \$99.2 billion and \$98.9 billion, respectively. Mining and mineral rents totalled \$68.9 billion. Renewable natural capital in our analysis consists of fisheries rents (\$74.2 billion) and forestry production (\$19.8 billion).

Table 1 summarizes descriptive statistics of resource depletions calculated from both the production and consumption perspectives for oil, coal, gas, mineral, forestry and fishery resources. Rows 1-2 describe national level data valued in millions of 2011 USD. Rows 3-4 describe per capita production and consumption based resource depletions. Per capita production based resource depletions (ranging from \$1.81 in Nepal to \$9,383.78 in Qatar) exhibit greater variation than their consumption based counterparts (ranging from \$6.76 in Malawi to \$1,187 in Luxembourg). This is due to the distribution of natural resources: a small number of countries have disproportionate natural capital endowments (e.g. major oil producing countries). Per capita differences (production minus consumption) depletions are described in the final row, ranging from -$1,151.87 in Luxembourg to $8,851.29 in Qatar. If production minus consumption depletions are greater (less) than 0, then the country is a net exporter (importer).

Table 1 Summary of Resource Depletions (total and per capita)

	Mean	St.Dev	min	max	skewness
Production*	7284.80	18143.57	2.24	112455.84	4.10
Consumption*	7230.72	20947.78	19.56	163429.73	6.08
Production** (per capita)	436.90	1382.53	1.81	9383.78	4.80
Consumption** (per capita)	229.97	247.95	6.76	1187.57	1.50
Prod – Cons** (per capita)	206.93	1281.88	-1151.97	8851.29	4.85

* values in millions of 2011 USD

** values in 2011 USD

Sample is 138 countries and regions. Taiwan and 'Rest of the world' (Antarctica, Bouvet Island, British Indian Ocean Territory, and French Southern Territories) are omitted due to lack of data.

Figure 1a-c depicts the combined value of per capita depletions across all oil, coal, gas, mineral, forestry and fishery resources. Figure 1a-b depict per capita production and consumption based depletions. Fig 1c illustrates the difference between per capita production and consumption depletions (specifically, production minus consumption)[1]. There are several striking features of these maps. First, Fig 1a-b convey different stories about the impact of national economies on global natural capital. The highest per capita production based depleting countries consist mainly of major oil producing nations such as Qatar ($9,384), Kuwait ($8,676), Brunei Darussalam ($6,405) and Norway ($5,866). Australia ($1,222), Canada ($938) and Russia ($707) also fall in the top 20. Countries with the highest consumption-based depletions per capita include Luxembourg (£1,188), Iceland ($1068), and Kuwait ($889). The difference map (Fig 1c) can be interpreted as the magnitude of 'policy blind spot' (Steininger et al. 2016) that would arise if policies were informed by only one of the production or consumption accounts. Negative (positive) values indicate per capita resource importers (exporters).

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[1] All values are in 2011 US dollars. Chloropleth class breaks (colour categories) correspond to a boxplot distribution The values for the six colour classifications are defined as follows (min, p25 – 1.5* iqr), (p25 - 1.5*iqr, p25], (p25, p50], (p50, p75], (p75, p75 + 1.5*iqr] and (p75 + 1.5*iqr, max], where iqr = interquartile range.

Figure 1 Production and Consumption Accounts for Natural Resource Depletions

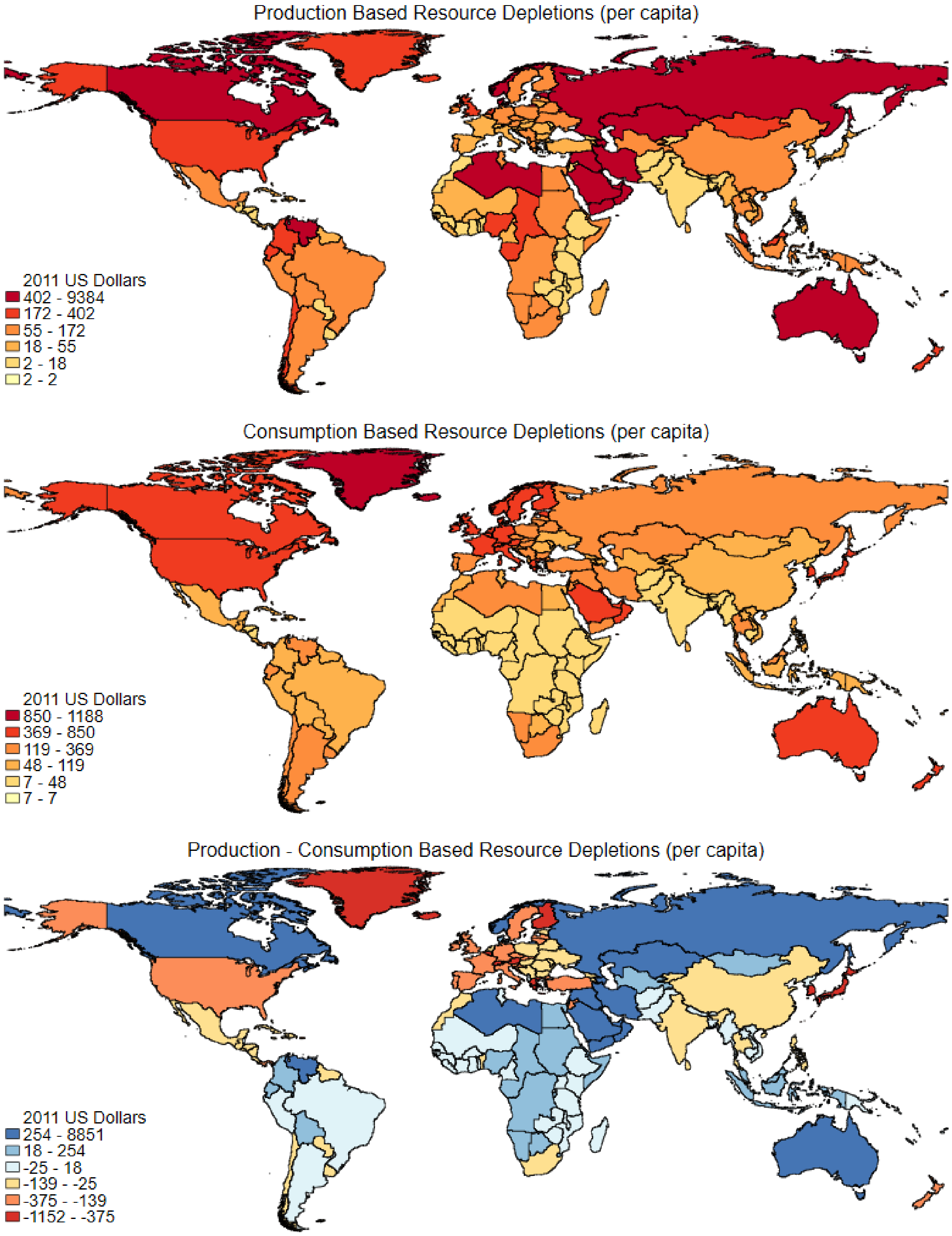


Figure 1a-b show per capita production and consumption based resource depletions. Fig 1c shows the difference (production minus consumption) in per capita resource depletions. Resources include forestry, fisheries, coal, oil, natural gas, and other mining (metal ores, uranium, gems). Values in 2011 USD. Greenhouse gas emissions are not included.

Examining national aggregates rather than per capita values, Figure 2 lists the 20 economies with the greatest divergence between the value of production and consumption based natural resource depletions. As in Fig 1, negative (positive) values represent net importers (exporters) of natural capital. It is noteworthy that both developed and developing countries appear as top resource importers and exporters. This suggests that the production versus consumption accounting gap for natural resources is important for countries at all stages of development. Unsurprisingly, major oil producing countries dominate the list of net exporters.

Figure 2 Natural resource depletions: the production versus consumption 'accounting gap'

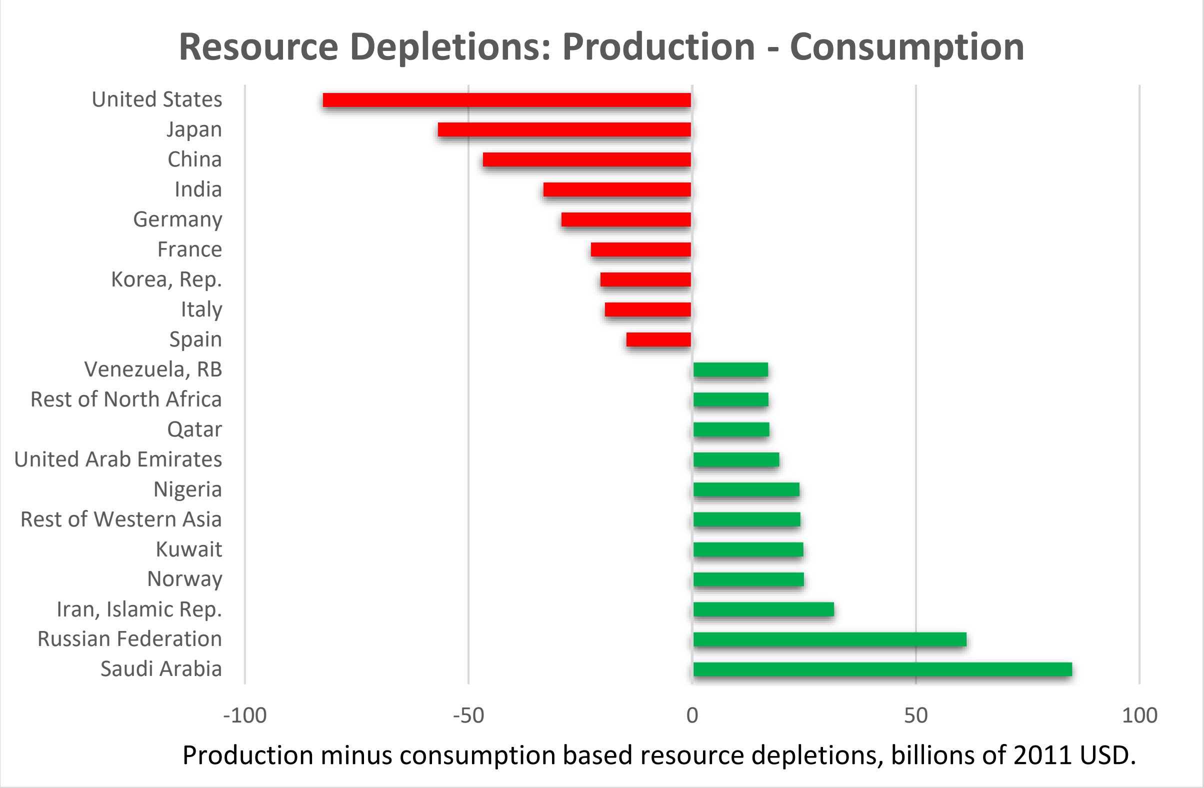


Figure 2 shows the 20 economies with the greatest difference between production- versus consumption-based resource depletions. Negative values indicate that consumption based depletions are greater than production based depletions. Resources include forestry, fisheries, coal, oil, natural gas, and other mining (metal ores, uranium, gems). Values in billions of 2011 USD. Rest of North Africa includes Algeria, Libya, and Western Sahara. Rest of Western Asia includes Iraq, Lebanon, Occupied Palestinian Territory, Syria, and Yemen.

Table 2 details national and per capita resource depletions for the 20 largest economies in 2011. Columns 3 and 5 show the value of resource rents calculated from the production and consumption perspectives, respectively. Showing these as a percentage of GDP, Columns 4 and 6 can be interpreted as the resource intensity of GDP. Column 7 shows the ratio of production to consumption depletions. Depletion ratios greater (less) than one indicate net resource exporters (importers). Columns 8 – 11 describe per capita resource depletion. Columns 8 and 10 reflect per capita depletions from the production and consumption perspectives, while columns 9 and 11 compare these to the average global citizen. Values greater than one indicate that per capita depletions are greater than the global average, while values less than one indicate the reverse.

Table 2. Production and consumption accounting for natural resource depletions

	GDP	Resource Depletions (millions of USD)					Per capita depletions & comparison to global average (GA)			
		Production		Consumption		Ratio	Production		Consumption	
		Value	% GDP	Value	% GDP	PBP/CBP	Per capita	P/GA	Per capita	C/GA
United States	15,517,926	80,863	0.52	163,430	1.05	0.49	259.46	1.80	524.38	3.64
China	7,572,554	112,456	1.49	159,277	2.10	0.71	83.66	0.58	118.50	0.82
Japan	6,157,460	5,091	0.08	61,921	1.01	0.08	39.83	0.28	484.39	3.36
Germany	3,757,698	6,656	0.18	35,908	0.96	0.19	82.92	0.57	447.31	3.10
France	2,862,680	2,846	0.10	25,446	0.89	0.11	43.55	0.30	389.42	2.70
United Kingdom	2,619,700	13,364	0.51	26,279	1.00	0.51	211.26	1.46	415.42	2.88
Brazil	2,616,202	19,250	0.74	21,847	0.84	0.88	96.89	0.67	109.96	0.76
Italy	2,276,292	2,899	0.13	22,368	0.98	0.13	48.83	0.34	376.69	2.61
Russian Federation	2,051,662	101,086	4.93	39,746	1.94	2.54	707.09	4.90	278.02	1.93
India	1,823,050	16,742	0.92	50,037	2.74	0.33	13.42	0.09	40.12	0.28
Canada	1,788,648	32,228	1.80	18,706	1.05	1.72	938.42	6.51	544.69	3.78
Spain	1,488,067	2,002	0.13	16,702	1.12	0.12	42.83	0.30	357.33	2.48
Australia	1,390,557	27,292	1.96	15,088	1.09	1.81	1,221.69	8.47	675.39	4.68
Korea, Republic Of	1,202,464	1,662	0.14	22,171	1.84	0.07	33.29	0.23	443.99	3.08
Mexico	1,171,188	8,441	0.72	12,707	1.08	0.66	70.88	0.49	106.70	0.74
Netherlands	893,757	3,991	0.45	6,234	0.70	0.64	239.07	1.66	373.44	2.59
Indonesia	892,969	29,584	3.31	21,790	2.44	1.36	120.40	0.83	88.68	0.61
Turkey	832,546	2,525	0.30	13,084	1.57	0.19	34.40	0.24	178.23	1.24
Switzerland	699,580	330	0.05	4,128	0.59	0.08	41.69	0.29	521.72	3.62
Saudi Arabia	671,239	101,097	15.06	16,139	2.40	6.26	3,580.16	24.83	571.55	3.96
World	72,642,218	1,006,192	1.37	1,006,192	1.37	1.00	144.67	1.00	144.67	1.00

Table 2 shows total and per capita resource depletions calculated via production and consumption approaches. 20 countries with the highest 2011 GDP are shown, alongside the whole world. Per capita depletion values are in 2011 US$, total depletion values are in millions of 2011 US$. Natural resources covered include forestry, fisheries, coal, oil, natural gas, and other mining (metal ores, uranium, gems, etc).

Gross world product in 2011 was $72.6 trillion USD, with a resource intensity of 1.37%. Dividing the value of resource depletions by global population gives per capita resource depletions for the global average citizen of $144.67 USD. The global per capita mean is equal for both production and consumption-based depletions, but the distribution around the mean is not. Per capita production based depletions have a standard deviation 1382.53, compared to 247.95 from the consumption perspective. This is largely driven by the unequal distribution of fossil fuel resources relative to the global population. The ratio of per capita production based depletions to the global average is highest in oil rich nations such as Qatar and Kuwait (65 and 60 times the global average) and lowest in Nepal (0.01 times the global average).

There are 39 countries for whom per capita consumption based depletions are more than twice the global average. The ratio is highest for Luxembourg and Kuwait (8.23 and 6.16 times the global average, respectively). It is possible that population statistics obscure these results. Both Luxembourg and Kuwait have small official domestic populations as commuters and migrant workers are not included in population data. For instance, while Luxembourg's consumption-based depletions per capita are 8.23 times the global average, the consumption based resource intensity of GDP is 1.03% (ranked 122nd of 140). Similarly, Kuwait's consumption-based depletions are 1.84% of GDP, similar to that of South Korea.

The G7 countries had a combined GDP of $40.8 trillion with production (consumption) based resource intensity of 0.54% (1.21%). Their combined per capita production based depletions were 76% of the global average while from the consumption based perspective they are 273% of the global average. The full table of results is available in Appendix 4.

Figure 3 provides a breakdown of per capita production and consumption-based depletions for each element of natural capital. Correlations between production and consumption depletions are strongest for fisheries ($\rho = 0.912$) and forestry ($\rho = 0.838$). Correlations for coal ($\rho = 0.409$), oil ($\rho = 0.429$), and natural gas ($\rho = 0.499$) are comparatively lower. The log scale suggests that variation across countries is substantial for non-renewables, but much less so for renewable natural capital such as fisheries and forestry. The line of equality (dashed grey line) indicates per capita production and consumption depletions are equal. Deviations from this line suggest that the two accounting perspectives provide different information about an economy's relationship to natural capital.

Figure 3 Per capita production and consumption depletions of natural capital resources

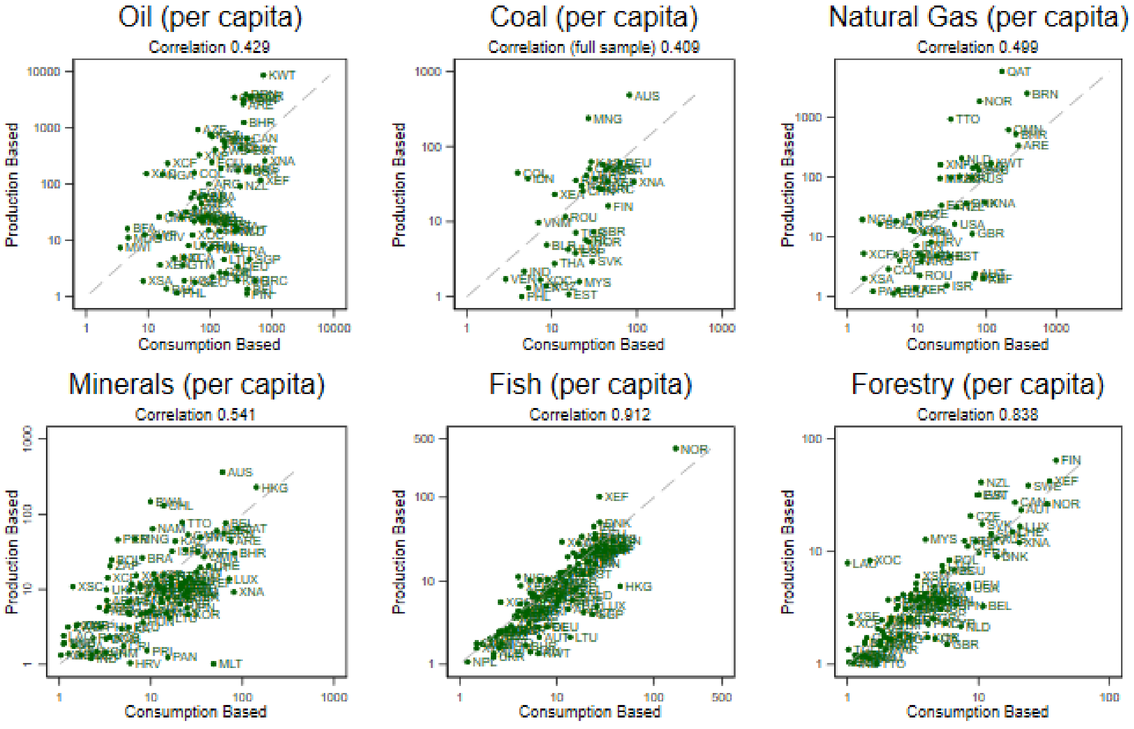


Figure 3 compares per capita PB versus CB depletions for a suite of natural capital resources. All values are in 2011 USD. Countries with per capita production based depletions less than $1.00 are omitted.

Table 3 details national and per capita greenhouse gas emissions for the 20 largest economies on 2011. Columns 3 and 5 show the value of GHG emissions calculated from the production and consumption perspectives, respectively. Columns 4 and 6 display these as a share of GDP and can be interpreted as the carbon intensity of GDP. Column 7 shows the ratio of production to consumption based emissions. Ratios greater (less) than one indicate net exporters (importers) of virtual carbon. Columns 8 and 10 reflect per capita emissions from the production and consumption perspectives, while columns 9 and 11 compare these to the global average citizen. Values greater (less) than one indicate that per capita emissions are greater (less) than the global average citizen's.

Using a mid-range carbon price of $150/tCO$_2$, global emissions (28,818 million tons) totalled $4.3 trillion, or 5.95% of gross world product, with global average per capita emissions of 4.13 tons or $619.56. 38 countries have CB per capita emissions greater than twice the global average and 50 countries for which it is less than half the global average. The G7's production ($2,293,801) and consumption ($2,284,398) emissions are similar, representing 5.63% and 5.60% of GDP, respectively. The notable outlier in terms of emissions intensity of GDP is China (14.34% and 11.88% from the production and consumption perspectives). The next highest is the US, at 4.94% of GDP (production) and 5.36% (consumption). Finally, G7 per capita production emissions are approximately double the global average with per capita consumption emissions 2.35 times the global average.

Table 3 Production and consumption accounting for greenhouse gas emissions

Production and Consumption Greenhouse Gas Emissions

		GHG emissions (millions of 2011 USD)					GHGs per capita & comparison to global average			
	GDP	Production		Consumption		Ratio	Production		Consumption	
		Value	% GDP	Value	% GDP	PBP/CBP	Per Capita	P/GA	Per Capita	C/GA
United States	15,517,926	766,199	4.94	832,509	5.36	0.92	2,458.42	3.97	2,671.18	4.31
China	7,572,554	1,086,166	14.34	899,264	11.88	1.21	808.08	1.30	669.03	1.08
Japan	6,157,460	154,512	2.51	183,623	2.98	0.84	1,208.70	1.95	1,436.43	2.32
Germany	3,757,698	104,199	2.77	126,065	3.35	0.83	1,298.02	2.10	1,570.41	2.53
France	2,862,680	53,681	1.88	73,923	2.58	0.73	821.54	1.33	1,131.31	1.83
United Kingdom	2,619,700	70,612	2.70	93,869	3.58	0.75	1,116.24	1.80	1,483.89	2.40
Brazil	2,616,202	55,799	2.13	68,656	2.62	0.81	280.84	0.45	345.55	0.56
Italy	2,276,292	58,432	2.57	75,145	3.30	0.78	984.05	1.59	1,265.51	2.04
Russian Federation	2,051,662	225,524	10.99	200,729	9.78	1.12	1,577.53	2.55	1,404.08	2.27
India	1,823,050	265,697	14.57	251,665	13.80	1.06	213.03	0.34	201.78	0.33
Canada	1,788,648	78,467	4.39	76,750	4.29	1.02	2,284.81	3.69	2,234.83	3.61
Spain	1,488,067	42,201	2.84	47,658	3.20	0.89	902.84	1.46	1,019.58	1.65
Australia	1,390,557	56,951	4.10	59,534	4.28	0.96	2,549.28	4.11	2,664.90	4.30
Korea, Republic Of	1,202,464	75,285	6.26	69,827	5.81	1.08	1,507.60	2.43	1,398.32	2.26
Mexico	1,171,188	63,615	5.43	66,656	5.69	0.95	534.17	0.86	559.71	0.90
Netherlands	893,757	25,539	2.86	24,935	2.79	1.02	1,529.89	2.47	1,493.71	2.41
Indonesia	892,969	58,064	6.50	63,876	7.15	0.91	236.31	0.38	259.97	0.42
Turkey	832,546	42,853	5.15	50,192	6.03	0.85	583.75	0.94	683.72	1.10
Switzerland	699,580	6,227	0.89	14,023	2.00	0.44	787.02	1.27	1,772.26	2.86
Saudi Arabia	671,239	54,766	8.16	57,669	8.59	0.95	1,939.44	3.13	2,042.26	3.30
World	72,642,218	4,322,741	5.95	4,322,741	5.95	1.00	619.56	1.00	619.56	1.00

Table 3 shows total and per capita GHG emissions calculated via production and consumption approaches. 20 countries with the highest 2011 GDP are shown, alongside the whole world. GHG emissions are valued at $150/tCO2. GDP, PB and CB emissions (columns 2, 3, and 5) are in millions of 2011 USD. Per capita emissions are in 2011 USD.

2.5. Discussion

The 17 sustainable development goals represent the growth and development objectives agreed by the global community (Griggs et al. 2014; Sachs et al. 2019). They are not explicitly framed within the wealth theory of sustainability, but there are considerable opportunities for overlap and mutual reinforcement. Goals 3, 4, and 5 on health and wellbeing, education, and gender equality clearly relate to elements of human capital. Goals 1, 2, and 10 on ending poverty, hunger and reducing inequalities entail obvious links to social and institutional capital, as do goals 16 (peace, justice and strong institutions) and 17 (partnerships for the goals). Goals 7, 9 and 11 on clean energy, industry and infrastructure, and sustainable cities and communities require investments in physical and human capital, and so on. The relationship between various forms of capital and achieving the SDGs is even more important when we consider interactions between SDGs and components of wealth. Strong institutions help deliver decent work and economic growth, which in turn contributes to affordable and clean energy systems, thus enabling progress on climate action (SDG 13).

Given the importance of broadly defined wealth to delivering the SDGs there is an opportunity for wealth accounts to directly inform progress towards achieving the SDGs. One obvious link relates to SDG 12, to “Ensure sustainable consumption and production patterns”. SDG 12.2 aims to “achieve the sustainable management and efficient use of natural resources” and entails two associated indicators (UN 2017):

SDG 12.2.1: Material footprint, material footprint per capita, and material footprint per GDP.

SDG 12.2.2: Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP.

The primary difference between the two indicators is how they deal with international supply chains. Material footprints (SDG 12.2.1) are a consumption-based measure that reflects the amount of material required along the supply chain to satisfy final demand, regardless of where those materials are sourced. In contrast, domestic material consumption (SDG 12.2.2) is (confusingly) a territorial or production-based measure calculated as domestic extraction plus imports minus exports. Both are typically measured in thousands of tonnes per year and for SDG reporting are aggregated to four categories: biomass, fossil fuels, metal ores, and non-metalic minerals (United Nations Statistics Division 2018).

There are good reasons for developing indicators in biophysical rather than monetary terms (Victor 2019). Biophysical accounts are a necessary first step to developing monetary accounts and are therefore unavoidable. Second, biophysical accounting units may be more directly applicable in a range of policy contexts (e.g. limiting fossil fuel extraction or setting fishing quotas). One of the chief motivations, however, is that the challenge of valuing natural capital rents is avoided entirely, and secular price fluctuations (arising for instance due to geopolitical events) do not lead to wild changes in the accounts.

However, the wealth theory of sustainability and subsequent wealth management rules require wealth depletions valued at the appropriate shadow prices rather than measured in physical flows. We provide a complementary accounting approach that links the conceptual background underpinning SDG 12 to the formal wealth theory of sustainability. Our production-based accounts align most closely with domestic material consumption, whilst our consumption-based accounts align with material footprints. By using resource rents rather than biophysical flows, our results are also relevant to those wishing to measure sustainability within the wealth framework.

Our results show that constructing accounts from both perspectives reveals different, yet equally important trends in natural capital depletions. Focusing exclusively on production accounts opens the potential for 'leakage' and ignores opportunities to influence resource management along the supply chain. Moreover, the suite of accounts developed here enables us to provide greater insight into the global nature of sustainability.

We argue that production and consumption accounts are useful and complementary tools for understanding the natural capital impacts and dependencies of nations. But their usefulness is not limited to sustainability and environmental policy. In fact, it may be the case that natural capital and wealth accounts more broadly are even more useful for assessing and guiding macroeconomic policies. Governments are beginning to develop extended public sector balance sheet accounts in order to better understand fiscal risks and add information to economic and fiscal outlooks. Public sector net debt and public sector net financial liabilities are familiar measures to macroeconomic policy makers, but some governments (e.g. UK and New Zealand) are beginning to explore more comprehensive measures.

Natural capital accounts are also important elements of the public sector balance sheet (PSBS), which if constructed well can greatly improve fiscal outlook and policy (IMF 2018). Complete PSBS can enrich fiscal policy by providing a more complete measure of public assets and liabilities (revealing opportunities for improved management). This improves the identification of risks (including tail-, transition-, and exchange-risks), and can improve fiscal policy making by enabling a systematic and more comprehensive evaluation of the impact of potential policies on public sector assets and liabilities (IMF 2018). Using the SEEA natural capital accounts in combination with a PSBS leverages the power of both. Sound balance sheet management facilitates increased revenues, reduced risks, and improved fiscal policy making. The IMF (2018, viii) argues that financial markets are increasingly paying attention to the entire government balance sheet and … strong balance sheets enhance economic resilience."

Natural capital accounts can improve balance sheet analysis in several ways:

- A better understanding of liabilities. Respiratory illness due to poor air quality can place a burden on the public finances either by reducing labour supply, reducing labour productivity, increasing burdens on publicly funded health systems, or some combination of the three. The risk is particularly acute in aging societies (Harris et al. 2019). The SEEA air emissions account records particulate emissions by resident economic units and type of substance, which can be used to assess the overall public liability arising from air pollution. See SEEA-CF 3.6.3 (UNSD 2017). Similarly, the SEEA Environmental Activity Account organises information on environmental protection expenditure and can improve estimates of how these liabilities might be affected by climate change.
- A more accurate reflection of future revenue. The SEEA Environmental Activity Account organises data on public sector revenues from environmental taxation. These accounts can shed light on the reliability of current revenues, the potential for future revenues, and the fiscal effect of asset stranding and other transition related risks.
- A more accurate reflection of public sector net worth. In most instances, government receipts from natural resources are treated as revenue, even when those funds come from the depletion of non-renewable natural capital. This overstates government revenues and inflates the net operating balance relative to the more accurate view that such depletions mimic the sale of nonfinancial assets. The SEEA accounts would record these depletions as reductions in wealth. Including natural capital stocks in the PSBS would help finance ministries and central banks 'stress test' environmental and technology scenarios around climate change and decarbonisation.
- The indirect impact of public policy in generating public goods, which build broad assets such as natural, social and other forms of intangible capital in addition to physical infrastructure, yield indirect returns in the form of higher future personal and corporate tax revenues generated through higher productivity.

The IMF's 2018 Fiscal Monitor focused on managing public wealth and notes that (i) public sector balance sheets have enabled economies to manage economic shocks, but that (ii) the treatment of natural resources within public sector balance sheets could be improved as they currently record natural resource depletions only as revenues rather than capital depletions. As more countries begin to produce public sector accounts, the treatment of natural capital within them will become increasingly important. This coincides with the revision and implementation of the UN System of Environmental Economic Accounts (SEEA), and in particular the Experimental Ecosystem Account (SEEA-EEA). Developing SEEA accounts alongside public sector balance sheets can greatly improve the measurement of public sector net worth. Any attempt to do so should also address the international trade dimension. For instance, international payments for ecosystem service schemes could provide revenue and affect the value of domestic natural capital assets. Alternatively, border taxes on virtual carbon could affect the value of fossil fuel resources. These public sector accounts are also useful for conducting intertemporal balance sheet analyses, which include the possibility of future taxation as a source of government revenue. This is a potential area where natural capital accounts could be particularly important, as environmental taxes may become more politically acceptable.

2.6. Conclusion

The wealth theory of sustainability suggests that maintaining living standards requires non-declining per capita wealth over time. Natural capital depletions represent a reduction in wealth. But in a globalised economy with long international supply chains, a question arises about where to attribute wealth depletions. Most wealth accounts adopt a territorial or production-based perspective. These describe trends in natural capital stocks within a country's national borders and are therefore relevant for calculating domestic per capita natural capital depletions. This paper investigates whether territorial natural capital accounts are fit for purpose when measuring national and global sustainability in an increasingly globalised world.

The discussion is centred around SDG 12 – sustainable consumption and production – and adds and responds to calls for more complete official statistics on the national and global dimensions of natural capital depletion. In the technical report on the SDG Index, Lafortune et al (2018, p15) note that measurement of SDG 12 relies on non-official data, which are needed "to gauge environmental spill over effects embodied into trade via input-output estimations".

We respond by developing a 140-region 57-sector Multi-Regional Input-Output model to describe natural capital flows embodied within international trade. The analysis enables us to measure the extent to which countries may be 'importing virtual sustainability' by depleting foreign rather than domestic natural capital. In so doing, we provide evidence to support the Sarkozy Commission's conjecture that a measurement approach "centred on national sustainabilities may be relevant for some dimensions of sustainability, but not for others" (Stiglitz et al. 2009a, p77).

The results confirmed that this is indeed the case. Our suite of accounts makes it possible to calculate the magnitude of the policy blind spot imposed by relying on just one accounting perspective. Globally, natural capital depletions of coal, oil, gas, minerals, timber, and fisheries totalled $1 trillion in 2011. The G7 countries had a combined GDP of $40.8 trillion with production (consumption) based resource intensity of 0.54% (1.21%). Their combined per capita production based depletions were 76% of the global average while from the consumption based perspective they are 273% of the global average.

The future of wealth accounting must make a stronger effort to reflect the role of globalisation – of goods, externalities, and policy responses – within official statistics. The regular construction of production and consumption based accounts for natural capital will be made much easier as countries start developing official statistics in-line with the UN System of Environmental Economic Accounts. Macroeconomic policy makers may be among the greatest beneficiaries of such information, as it would enable a more genuine assessment of the public sector balance sheet. The overarching conclusion is that perspective matters in developing accounts. Afterall, what we observe is not the economy itself, but the economy exposed to our method of accounting.

3. CARBON ACCOUNTS FOR MEASURING SUSTAINABILITY UNDER GLOBALIZATION

3.1. Abstract:

The explosive growth of international trade – from 24-61% of gross world product in the last half century – means that traded goods and services now account for 20-33% of global greenhouse gas emissions. There are severe implications for the development, measurement, and enforcement of global carbon and sustainability policy. Who is responsible for emissions released along the global supply chain? Is it producing and exporting countries like India and China? Or are rich countries ultimately liable for the carbon footprint of high-consumption lifestyles? We expose multiple shortcomings of the current approach to carbon accounting. First, by confusing the location of emissions with the location of climate damages, it overlooks fundamental tenets of climate science. Second, by failing to address globalization, it distorts not only the ethical and legal underpinnings, but also the real-world efficacy of international climate policy. And finally, it has so far failed to reach its potential to inform sustainability theory, accounting, policy, and science. We develop a 57-sector 140-region Multi-Regional Input-Output (MRIO) model to address these shortcomings. We trace virtual carbon flows along each step of the global supply chain, and construct GHG accounts according to multiple attribution rules. In combination, this suite of accounts provides a more nuanced and holistic understanding of the carbon footprint of nations. We introduce a novel procedure for linking emissions to the location of climate losses, and provide a global CO_2e account that is fully consistent with sustainability theory and science. Results are reported in terms of contributions to national- vs global-level sustainability, and progress towards multiple Sustainable Development Goals.

3.2. 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 (Weitzman 1976; Hartwick 1977; Dasgupta and Heal 1979; Solow 1986; Dasgupta 2001; Hamilton and Hepburn 2017). 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 off as the present' requires that comprehensive wealth is non-declining over time. Following initial empirical contributions by Pearce and Atkinson (1993b), wealth accounting research seeks to measure the extent to which individual countries adhere to the capital management rule (Pearce and Atkinson 1993b; Hamilton and Hepburn 2017; Fenichel et al. 2018; Lange 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 regions (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) (Kartha et al. 2009; Marques et al. 2012; Raupach et al. 2014; Steininger et al. 2014).

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 and 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).

3.3. Carbon accounting within a sustainability framework

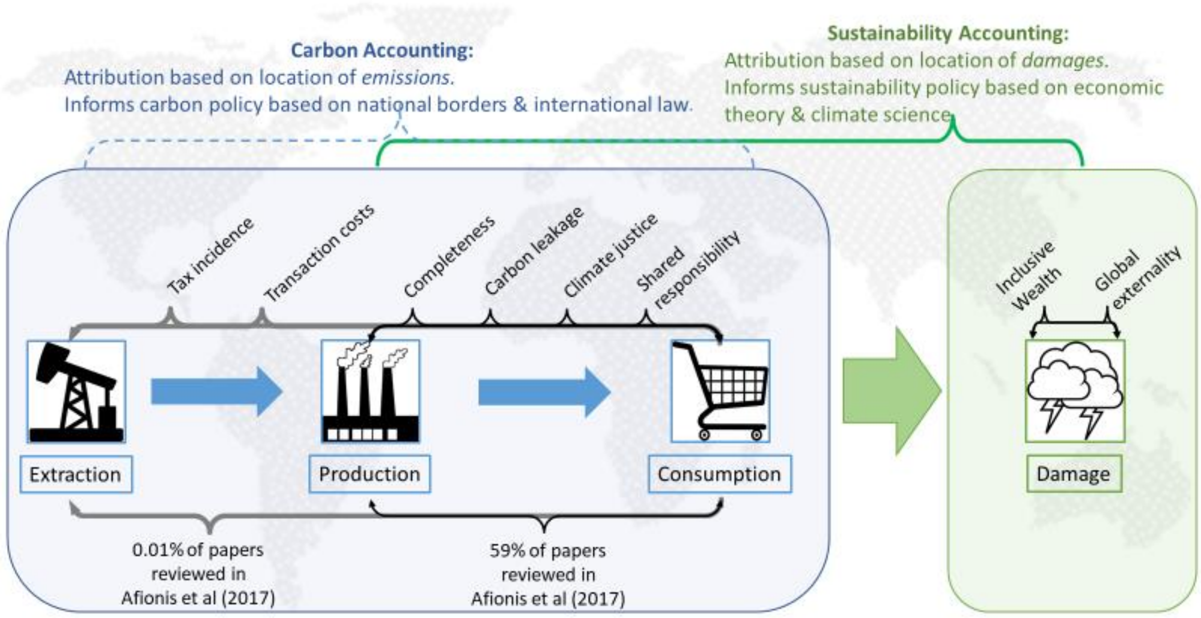
Accounts are tools for telling stories over time (Coyle 2015). Ideally, the information contained in these stories is driven by the specific goals and interests of decision-making end users. Formal accounting procedures are then developed to identify, collect, and report information material to those 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 4) (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. 2009, 2011; Davis and Caldeira 2010); 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 4). While sustainability accounts must incorporate emissions, they need not be restricted by the existence of accounts designed for other purposes.

Figure 4 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 (Arrow et al. 2012) and science (Ricke et al. 2018). It depicts 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. Damages refer to the welfare losses that each country will suffer as a result of global carbon emissions. This is empirically and conceptually different from the amount that each country contributes to global damages (ie national emissions). As Arrow et al. (Arrow et al. 2012, p. 328) demonstrate, the appropriate adjustment to wealth is not a nation's emissions, but rather "the damages caused to a country by anthropogenic climate change".

Figure 4 Emissions accounting along global supply chains



3.4. From carbon accounting to sustainability accounting

Most wealth accounts incorporate emissions according to the PB approach (World Bank 2006, 2011; Lange et al. 2018). PB adjustments to inclusive wealth accounts would be appropriate if (i) the damages from climate change only accrued to the country that created the emissions, or (ii) a global compensation mechanism ensured that each fully compensated countries for the damages they suffer. Even the compensation mechanism would require that the correct social cost of carbon be charged in the polluting country and distributed to the country facing the damages. Identifying the latter still requires a damage-based account. Given that neither (i) or (ii) hold in the real world, 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 and UNEP 2012, 2014; Managi and 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 and 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 (Peters and Hertwich 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.

3.4.1. Calculating country-level damages

Empirical applications of Arrow et al's (2012) 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) 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 and Boyer 2000, 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 and Boyer 2000, p11). 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.

3.4.2. 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.

3.5. 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 for the year 2011[2]. Two chief advantages of GTAP are that it is balanced for use at different scales of analysis and that sectoral disaggregation is harmonised across regions. As a result, GTAP databases have become a mainstay in the carbon accounting literature.

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 to which an emissions growth function is applied as in Ahmed et al. (2014). The MRIO model is described in Appendix 1.

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.

3.5.1. 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 and Botzen 2014; Heal and Millner 2014; Nordhaus 2017; Ricke et al. 2018) a globally agreed value for carbon emissions remains elusive. Nordhaus (2017) uses DICE to calculated a SCC of \$31/tCO_2. 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

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[2] This is the same input-output model as described in Section 2.4.

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. 2014a). 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.

3.5.2. 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

3.6. 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 under informed.

Table 4 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. Country-level coefficients for the RICE model are calculated following the method set out in the Inclusive Wealth Reports (UNU-IHDP and UNEP 2014). RICE aggregates to 8 global regions and country-level impacts are calculated as the proportion of each country's GDP in the regional GDP total. PB and 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 4 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 4. 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 5 highlights (dis)agreement – the extent to which accounts convey the same or different information – between accounting perspectives. This is a proxy indicator for the extent to which each accounting perspective tells us something different about the world. If all perspectives were very highly correlated, an argument could be made that they do not convey enough unique information to justify the additional effort to compile them. That this is not the case (ie low correlation, or high ‘disagreement’) suggests that the perspectives do convey unique insights. 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.

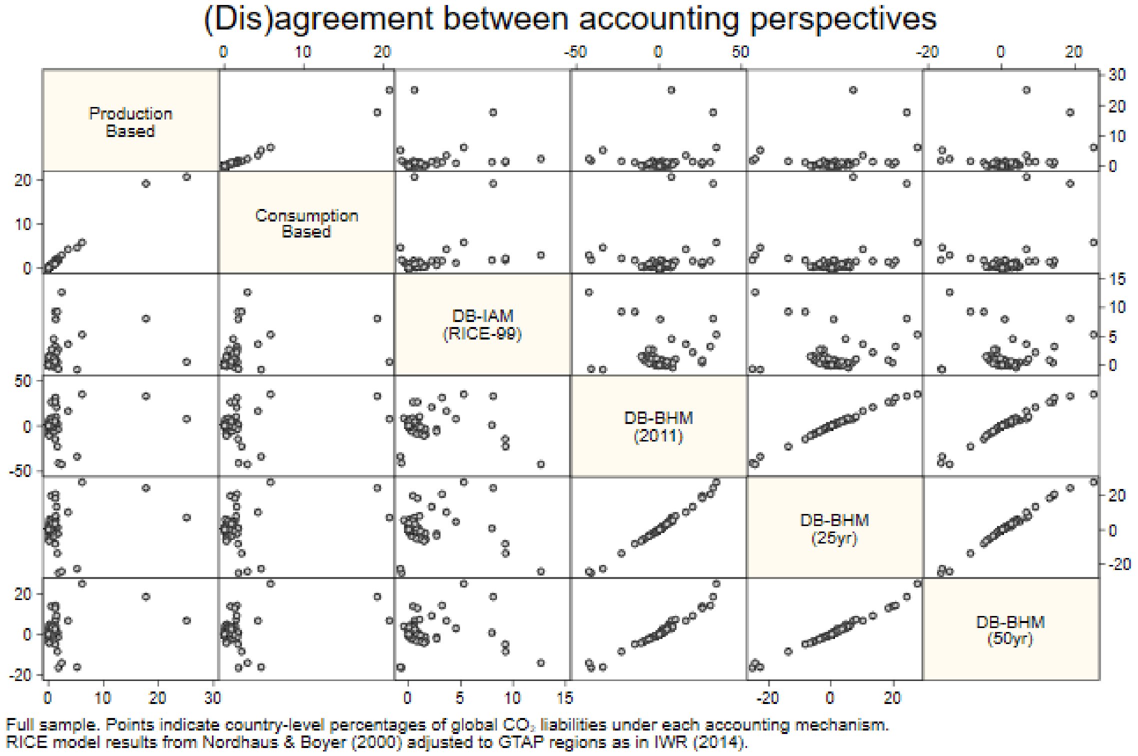
Table 5 Correlations between emissions accounting approaches

			Damage			
				Burke et al (2015)		
	Production Based	**Consumption Based**	**IAM**	**BHM (2011)**	**BHM (25 yr)**	**BHM (50 yr)**
Production Based	1					
Consumption Based	0.99*	1				
Damage Based (IWR)	0.32*	0.39*	1			
Damage BHM (2011)	0.21	0.23*	-0.09	1		
Damage BHM (25 yr)	0.26*	0.29*	-0.03	0.99*	1	
Damage BHM (50 yr)	0.31*	0.34*	0.04	0.97*	0.99*	1

Table 5. 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 5 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 5 Comparison of country-level attribution coefficients

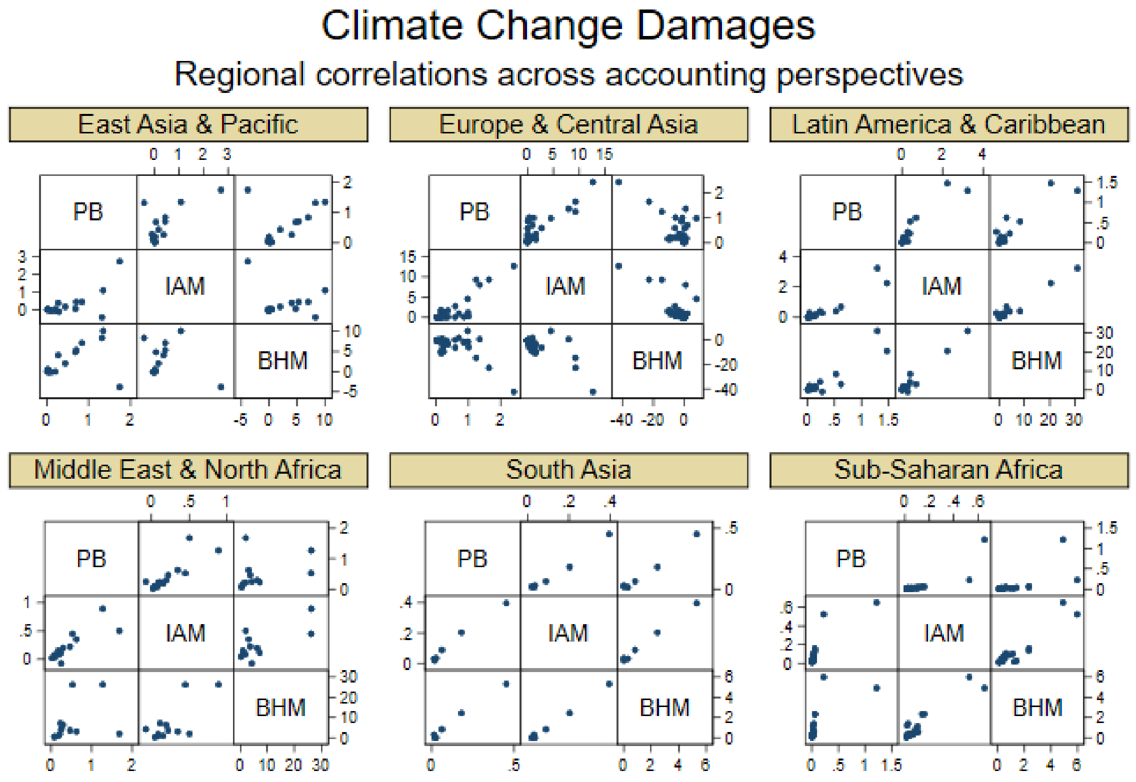

(Dis)agreement between accounting perspectives

Full sample. Points indicate country-level percentages of global CO_2 liabilities under each accounting mechanism.
RICE model results from Nordhaus & Boyer (2000) adjusted to GTAP regions as in IWR (2014).

Figure 5. 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 6 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 6, Europe & Central Asia). This is largely because Burke et al. (2015) find potential output gains due to warming in currently cold countries. There is 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 because BHM results indicate substantial benefits to mild warming across northern Europe, whereas RICE results suggest these countries will be made unambiguously poorer.

Figure 6 Attribution coefficients by region



North American region dropped (n=2). Outliers removed (China, USA, Russia, Japan, and India).

Figure 6. 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 5 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).

3.6.1. Cross-country Comparisons

Table 6 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. PB and CB accounts can be thought of as damages caused, whereas the DB accounts refer to damages incurred[3].

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[3] I am grateful to Ben Groom for providing this succinct interpretation.

Table 6 Attribution coefficients for selected countries under different accounting perspectives

		PERCENTAGE OF GLOBAL EMISSIONS 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.

3.6.2. Production versus Consumption Based Accounts

Figure 4 showed that the carbon accounting debate largely focuses on the distinction between PB and CB approaches (Afionis et al. 2017). Table 5 and Figure 5 suggest a degree of agreement between PB and CB accounts. But Figure 7 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 7 The accounting gap: Production minus Consumption Based Emissions

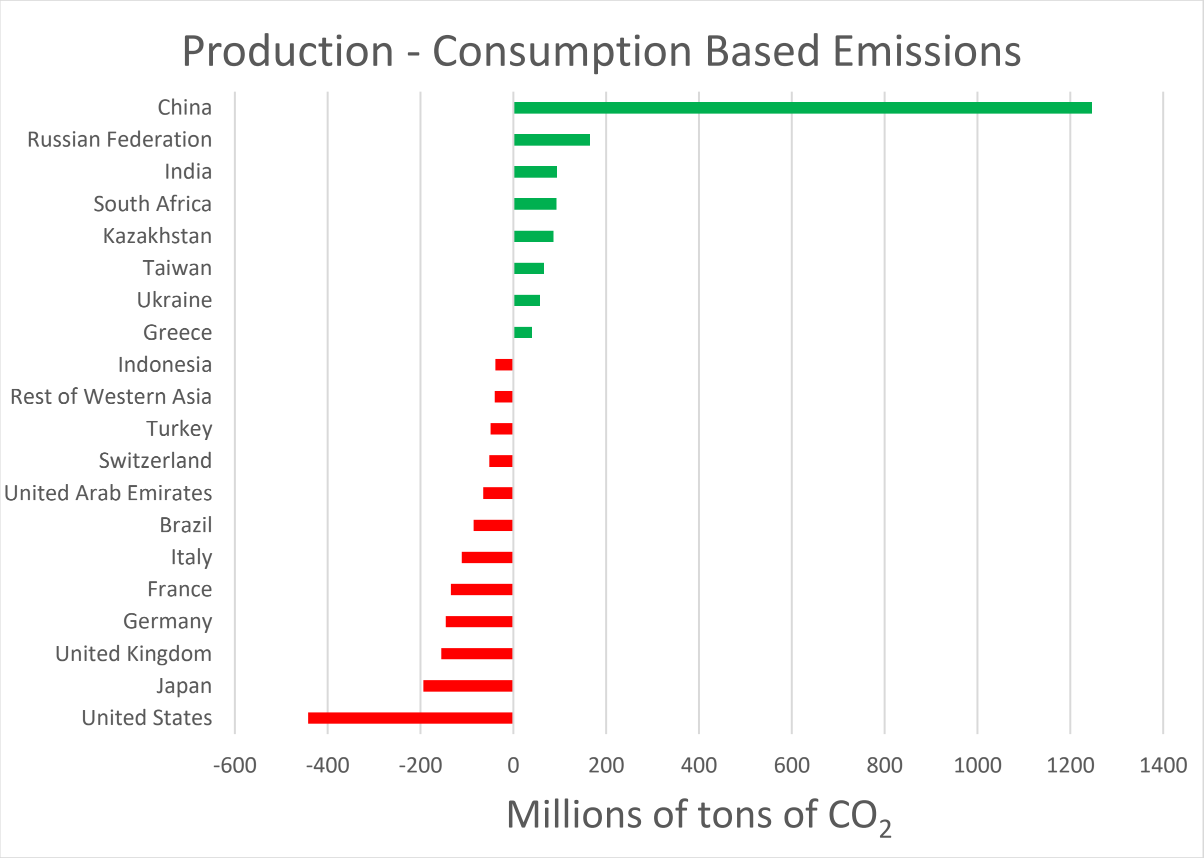


Figure 7. The 20 countries with the greatest absolute value difference between PB and CB emissions. Values in millions of tons of CO_2 for 2011. Rest of Western Asia includes Iraq, Lebanon, Occupied Palestinian Territory, Syria, and Yemen. Positive (negative) values indicate the country is a net exporter (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. 7 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.

Figures 8 and 9 map PB and CB 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 8 Country-specific shares of global emissions under production-based accounting

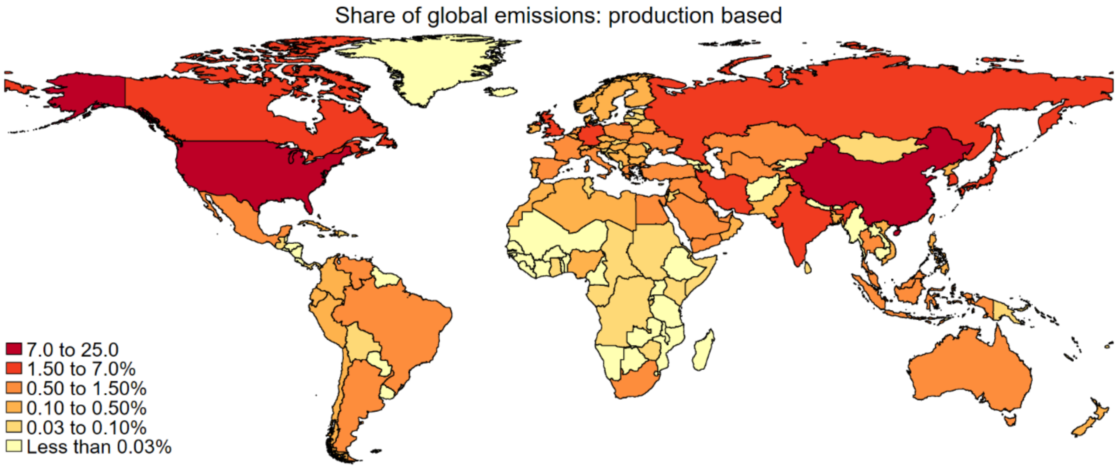
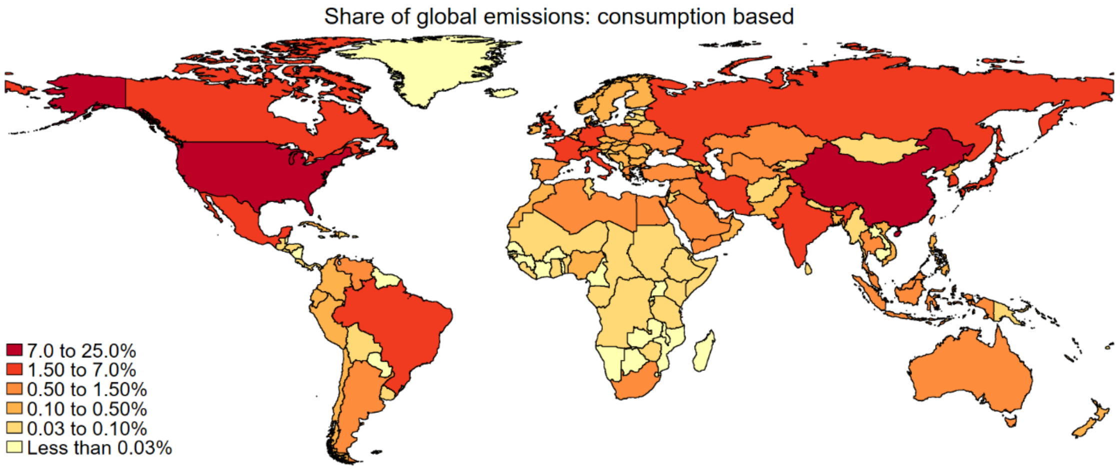


Figure 9 Country-specific shares of global emissions under consumption based accounting



Figures 8-9. 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.

3.6.3. Damage based accounts

Figure 10 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.

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.

Figure 10 Country-specific shares of global emissions under damage based perspective (BHM 2011)

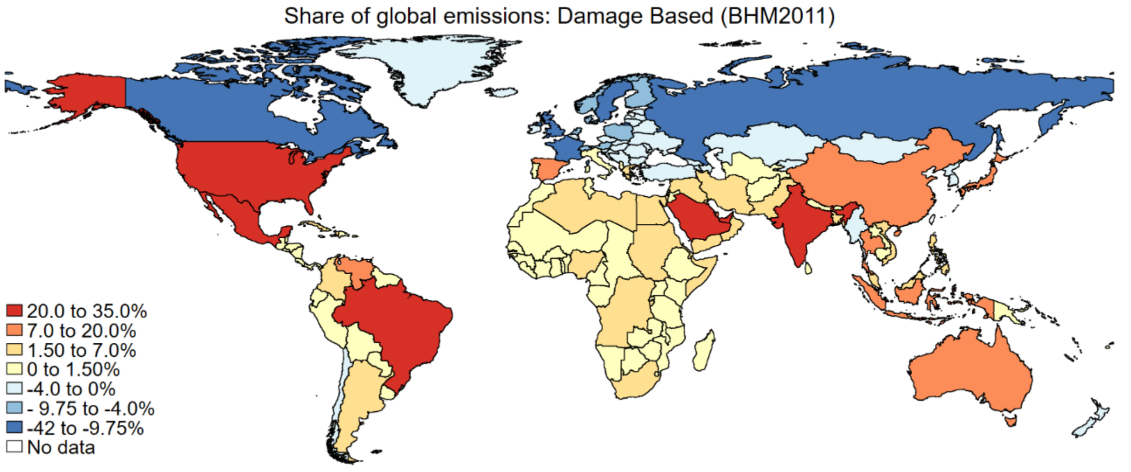


Figure 10 shows country-level GHG attribution coefficients calculated according to the BHM2011 variant of damage based accounts. Negative damages (blue) are modelled benefits from mild warming. Impacts are aggregated to match the 140 regions contained in GTAPv9 for comparison with other results.

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.

3.6.4. 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 11 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 11 indicate highly and similarly unequal global distribution of GHG attributions.

Figure 11 Inequality in emissions attributions: PB, CB, and DB-IAM accounting perspectives.

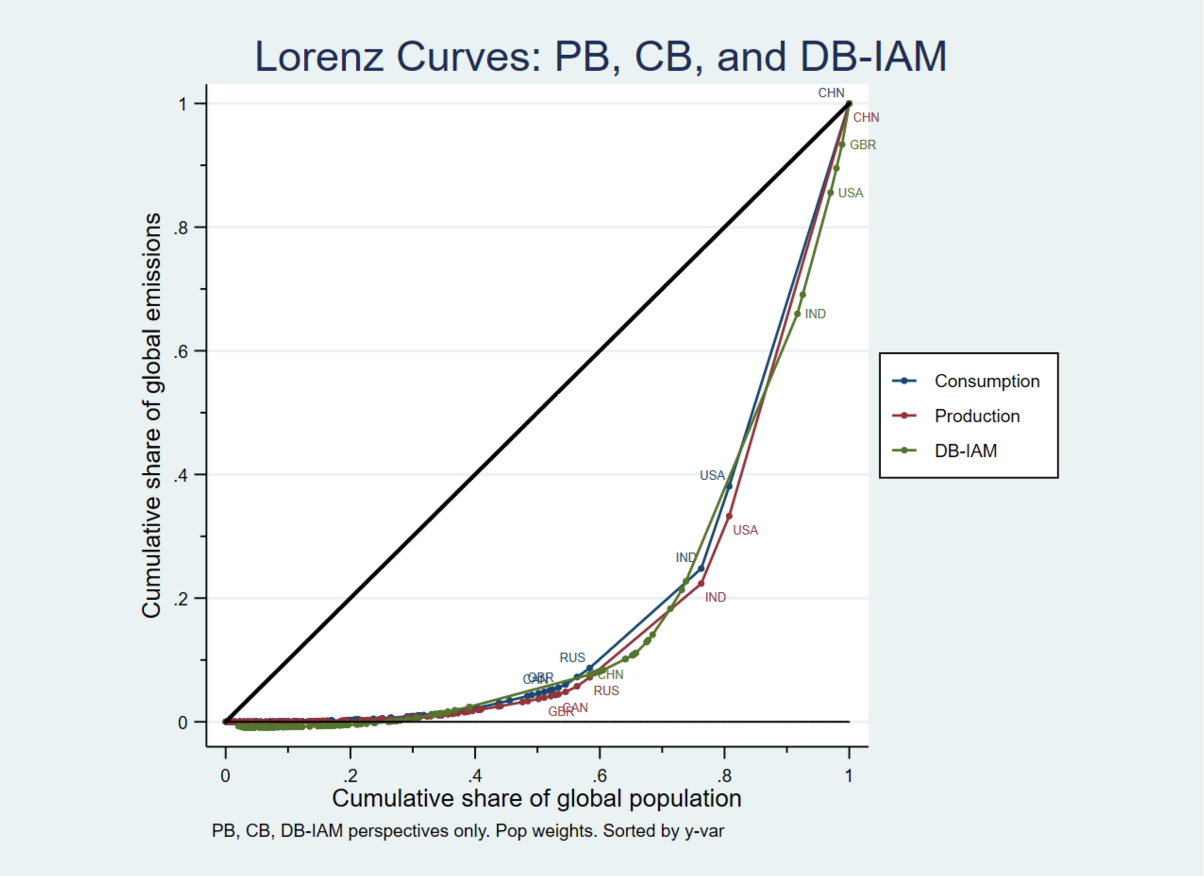


Figure 11. Population-weighted Lorenz Curves for PB, CB, and DB-IAM accounting perspectives suggest that each accounting perspective describes similar inequality in the distribution of GHG allocations. The black line indicates the line of perfect equality. Deviations to the lower right indicate rising 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 12 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 12 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 12 Inequality in emissions attributions: all perspectives

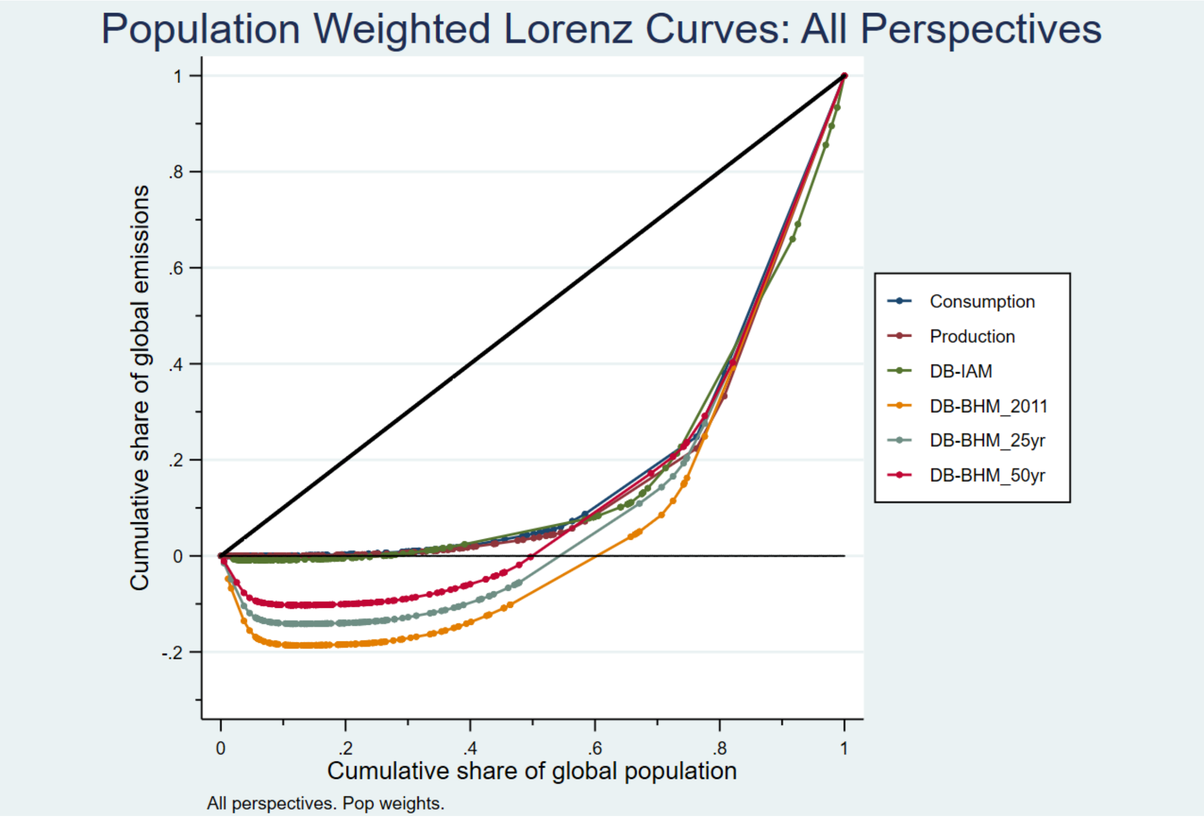


Figure 12. Lorenz curves illustrate inequality in emissions attributions across all accounting perspectives. DB-BHM_2011, DB-BHM_25yr, and DB-BHM_50yr refer to damage based coefficients calculated according to the 2011, 25-year, and 50-year slices of country-level climate impacts from Burke et al (2015), respectively. The black line indicates the line of perfect equality. Deviations to the lower right indicate rising inequality in the distribution.

3.7. Discussion and 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. 2011; Steininger et al. 2016) 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.

Consistent with the wealth theory, the damages calculated here represent a loss of wealth, or productive capacity. An interesting question for further work would be to clarify which component of wealth these losses should be attributed to. A strong case could be made that because emissions represent a depletion of climate capital, that they would fall under the natural capital umbrella. However, the social cost of carbon theoretically incorporates the full set of impacts arising from a unit of carbon. If climate change impacts human capital (eg. through reduced cognitive capacity and therefore lower labour productivity), physical capital (e.g. via property damages due to flood and fire), or social capital (e.g. via the impact of mass migration), then attributing the loss exclusively to natural capital would be misleading. In aggregate terms, this may not be an issue if the weak sustainability approach of perfect substitutability is assumed. However, to the extent that the capitals interact and may face limited substitutability, this has the potential to become a serious concern.

The various complementary accounts presented here could be used to build a dashboard of GHG accounts for guiding and evaluating climate policy. The more complete information they convey may help to reduce policy blind spots, motivate more aggressive climate action, and identify opportunities for coordination and collaboration in climate policy. Coordination failures are widely recognized as obstacles to adopting stringent emissions policies. For instance, a PB account shows that at 400Mt CO_2e, Australia emits just 1.3% of global emissions – a fact that is often cited in to suggest that unilateral climate policy in Australia would hurt the economy without having much impact on climate change overall. But in per capita terms, Australians emit 3.37 time more CO_2 and 4.15 more GHGs than the global average citizen. Moreover, Australia's fossil fuel exports (largely of coal and liquid natural gas) introduce a further 565.72 Mt CO_2e into the global supply chain. Finally, the DB account shows that Australia is expected to incur between 4% and 8% of all climate damages. With just one-third of one percent of the global population, this means that Australia's per capital loss of wealth due to climate change may be 12 to 24 times greater than that of the average global citizen. Focusing exclusively on the PB account would ignore the incentive Australians have to lobby for global action, given their disproportionate exposure to climate damages. Moreover, Australia could also have an impact through its exports. With a comparative advantage in research and engineering, it could take a leadership role in developing and diffusing green technology throughout South East Asia (Agarwala 2020). Thus, countries that may appear 'too small to make a difference' from one accounting perspective, could be significant players in different areas of the dashboard.

Beyond the dashboard, the suite of accounts is relevant to measuring progress across 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 10, and the resulting Lorenz curves in Fig 12. 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 provide 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.

3.8. Conclusions

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 emissions implicitly embodied within a country's final demand. We place this debate within the broader context of sustainability accounting and develop extended accounts to reflect the wealth impacts of carbon externalities. 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. They 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, ignoring the location of wealth depletions. The failure to address globalization and growth 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 (Nordhaus and Boyer 2000) 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.

4. MEASURING SUSTAINABILITY WITH THE SUSTAINABLE DEVELOPMENT GOALS: PRINCIPLE, PRINCIPAL, AND PRACTICE

4.1. Introduction

This paper examines whether the sustainable development goals *in practice* deliver the paradigm shift they represent *in principle.* The sustainable development goals (SDGs) provide the overarching framework of the 2030 international development agenda. Combined, the 17 SDGs, 169 targets, and 232 unique indicators provide the benchmark against which national and global sustainability will be measured. They are the North Star of the international community (Wackernagel et al. 2017). But to what extent do the SDGs truly re-orient and provide a new direction for the global political economy? This paper examines the extent to which measured progress towards achieving the SDGs represents a departure from 'development as usual'.

Amidst many competing and complementary definitions (Böhringer and Jochem 2007; Atkinson et al. 2014), the SDGs and associated indicators effectively 'reveal' the global community's adopted definition of sustainable development. The goals are intended to represent a new direction, a re-orientation of the global political economy towards a system that delivers for people, planet, and prosperity (Griggs et al. 2013). Inherent within them is an acknowledgement that development is a multidimensional challenge requiring integrated progress across multiple objectives for all countries (Obersteiner et al. 2016; Stafford-Smith et al. 2017; Breuer et al. 2019).

The goals move beyond the North-South development dichotomy which styles development as something to which poor countries aspire and wealthy countries ante up (Caballero 2019). Some of the world's wealthiest countries still face "major challenges" across goals on reduced inequalities and sustainable consumption and production (Sachs et al. 2019). A related and central feature of the SDGs is that they integrate concern for the environment across the full suite of goals, rather than separating 'environmental' and 'economic' objectives (Elder and Olsen 2019). Breaking down the barrier between the environment and development communities in this way is a substantial structural achievement for the 2030 Agenda (Caballero 2019).

But for all their strengths, the SDGs also face serious challenges. A perennial objection, common to all alternatives and complements to GDP, is essentially an argument for business as usual. Its logic is succinct. If the new measure is well correlated with GDP, it offers little new information. If it is not, then it ignores too much relevant information. Either way, per capita GDP is still the best measure around. In their simplest form, objections on these grounds are both defeatist and useless in the pursuit of sustainability (however defined), and robust rebuttals have been provided by leading economists (Nordhaus and Tobin 1972; Weitzman 1976; Sen 1983; Stiglitz et al. 2009a; Coyle 2015). Whilst it would be problematic if the SDGs could be compressed to a single indicator such as per capita GDP, the research set out here joins a global evidence base confirming this is not the case. A parallel question posed by Thomas Schelling (1992) concerns whether poor countries should sacrifice growth to reduce e.g. climate change, or whether they should develop at all costs and face the environmental consequences later, as richer economies. The analysis attempts to shed light on both of these questions: does SDG performance genuinely go 'beyond GDP' and, if SDG performance is the globally agreed definition of sustainable development, should countries attempt to achieve it by a narrow focus on per capita GDP growth or should they pursue broader environmental and social objectives as well?

Reducing poverty and raising material living standards for the world's poorest are development necessities, but will likely add to environmental pressures for at least the short- to medium-run. Trade-offs between biodiversity conservation and human wellbeing are a constant challenge to meeting ecological targets (McShane et al. 2011; Agarwala et al. 2014b; Milner-Gulland et al. 2014). Strategies for ending hunger (SDG 2) and ensuring affordable food can conflict with policies to conserve terrestrial ecosystems (SDG 15). Indeed many other trade-offs can be identified – between access to energy and greenhouse gas emissions (Fuso Nerini et al. 2018), between development aid and the development of democracy (Deaton 2013), and between enhancing domestic versus global sustainability (Atkinson et al. 2012; Dupuy and Agarwala 2014). Overall, the goal most frequently associated with trade-offs is SDG 12, on sustainable consumption and production (Pradhan et al. 2017). A chief contribution of this paper is to formally identify trade-offs and synergies between the goals using established statistical methods. A key concern is whether the SDGs can reconcile the need for large improvements in material living standards with the need for large reductions in environmental impacts.

I start from the position that sustainability is a latent concept. It has no obvious unit of measure, no universally accepted definition, and the breadth of topics it encompasses inevitably leads to a range of synergies and trade-offs. Sustainability cannot be observed. But we can observe many of its components and by analysing them, contribute to the knowledge base. In short, sustainability is a multidimensional challenge and to understand it requires multidimensional statistics. This paper employs established latent variable techniques for reducing the dimensionality of complex data into a manageable set of variables. Principal components analysis (PCA) is a useful tool for reducing the dimensionality of large dataset whilst retaining maximum information (Bartholomew et al. 2008; Jollife and Cadima 2016; Lever et al. 2017). It has applications across myriad disciplines, and has been used in contexts ranging from measuring and defining social capital and environmental performance (Morse 2018; Wealth Economy 2019) to identifying and classifying the earliest mammalian species (Gill et al. 2014).

I conduct PCA on data provided by the SDG Index (Sachs et al. 2019). Developed by Bertelsmann Stiftung and the Sustainable Development Solutions Network, the SDG Index measures country-level performance on each of the 17 SDGs. It is not an official UN Standard, but is audited by the European Commission Joint Research Centre (Papadimitriou et al. 2019). The 2019 Index covers 162 countries and includes a total 114 indicators (Lafortune et al. 2018; Sachs et al. 2019). There are at least four potential results:

1. **Mission failed**: PCA reveals a single component explaining the vast majority of total variation across the SDG scores, and which clearly distinguishes countries by per capita GDP. The remaining components describe very little variation so differences in SDG performance can be explained by differences in per capita GDP. The distance between SDG ambition and reality is high, and the best single measure of development is still per capita GDP.
2. **Mission impossible**: PCA reveals a dominant single component that contrasts ‘economic’ performance against environmental damage. At one end are wealthy but environmentally damaging economies, and at the other countries are too poor to make a footprint. In this outcome, the SDGs perfectly describe an environment versus development dichotomy, and the social and governance elements of the SDG agenda have little role. This would be damning result for the SDGs, which depend on the possibility of decoupling economic growth from environmental destruction, and would lend credence to the ‘de-growth’ argument.
3. **Mission irrelevant** or ‘development by silos’: There are 17 principal components, each describing 1/17th of the total original variance. The goals are completely independent and progress towards any one of them tells us nothing about progress towards the others. Each goal may be pursued independently and there is no scope for synergy or risk of trade-off[4].
4. **Mission accomplished**: The SDGs are multidimensional in practice, as well as in principle. Several components are required to explain the variation across SDG scores and they have credible interpretations. Per capita GDP alone is an insufficient proxy for SDG performance and environmental, social, and economic objectives are clearly evident in the components. If a small number of components describes most of the variation, then there is a degree of

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[4] An interesting alternative interpretation of this outcome is that the method has simply failed, on the grounds that we know there are important synergies between some of the goals which should be picked up in the analysis.

synergy and complementarity among goals and SDG performance entails success in multiple domains. Trade-offs between goals may also be evident and the analysis provides insight into what these may be.

This paper's chief contribution is to examine the extent to which the SDGs and associated indicators represent a truly new direction for the international development community, and if so, to offer an empirically defensible overview of what that new direction entails. Numerous reviews have found trade-offs and synergies among the goals. Some of these entail detailed models, others merely analyse the textual descriptions of the goals and indicators themselves. The approach taken here uses principal components analysis to elucidate and describe statistical relationships between the goals. Data comes from the SDG Index, which is the leading, global benchmark for measuring SDG performance. The inductive approach taken here is made possible by recent data that was unavailable to previous studies. Longer time series would permit more detailed statistical analysis, but sufficient data now exists to conduct early analysis into core themes across SDG measurement. However, results should be interpreted with caution. PCA interpretation entails a subjective element: relationships can be informative, but can also be spurious. Finally, it is likely that some discrepancy exists between what an SDG attempts to measure in principle, and what the available data actually measures in practice. Because this is a data-driven exercise, my findings are subject to all the caveats and contingencies that apply where measurements are imperfect proxies for the variable of interest.

The research is timely in that it coincides with ongoing discussions within the Inter-Agency Expert Group on the SDGs, with the UN Statistics Division, and between National Statistical Offices, think tanks, businesses, non-governmental organisations, and academics. Many of the official indicators listed in the SDGs still lack official statistical definitions and as such are under continuous review. The UN Statistical Commission will conduct is comprehensive review of the official SDG indicators at its 51st session in 2020 (and again in 2025). By examining principal components derived from the current stock of indicators for which data does exist, we can identify priorities for the development of new ones. The headline result is that per capita GDP accounts for only about half of the SDG scores of nations, meaning (i) about half of SDG performance is uncorrelated with per capita GDP and (ii) if we accepted the SDGs as the measure of progress, then development strategies based on a narrow pursuit of GDP growth would only get us about half way there.

The next section provides an overview of the SDGs and their measurement. Sections 3 and 4 describe the method and data. Section 5 describes results and is followed by a discussion of lessons learned and policy implications. A brief final section concludes.

4.2. Context

This research is concerned with the distance between the ambition of the SDGs and the reality of the indicators. For clarity, the goals and brief descriptions are listed in Table 7[5]. Progress towards the goals is defined in terms of meeting targets, which is in turn measured by individual indicators. A striking feature, common to all the goals is that their titles and brief descriptions are easy to grasp conceptually, but difficult to define concretely. It falls to countries, practitioners, and sustainability researchers to try to translate lofty goals into statistical measures. Data collection is a major challenge in implementing and monitoring SDG progress. Breuer et al (2019) note that given the complexity of interconnections within and between goals and the magnitude of the measurement challenge, policy makers may be tempted to continue with business as usual and hope that positive outcomes will eventually match official SDG indicators. Indeed, coordination costs may be high. Galli et al (2018) found that in Montenegro, 26 institutions handle data for assessing just 137 (56.8%) of the official SDG indicators.

Nor are the indicators necessarily well defined. The UN Inter-Agency Expert Group on the SDGs (IAEG-SDG) categorizes the official indicators into three tiers based on the quality of statistical methodology and data coverage (IAEG-SDGs 2019):

- Tier I: Indicator is conceptually clear, has an internationally established methodology, data are regularly produced by countries for at least 50% of countries and of the population in every region where the indicator is relevant
- Tier II: Indicator is conceptually clear, has an internationally established methodology, but data are not regularly produced by countries
- Tier III: No international established methodology or standards are available yet, but they are being (or will be) developed or tested.

As of the September 2019 IAEG-SDG update, there are 104 Tier I indicators, 89 Tier II Indicators, and 33 Tier III indicators (with an additional 6 indicators that have components categorized in different tiers). As official SDG data coverage becomes stronger, the relationships shown in the present analysis can be expected to change.

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[5] Three reference documents are useful for following and interpreting this research. Table 7 provides a list of SDGs with brief descriptions. The official UN list of goals and targets is here: https://undocs.org/A/RES/71/313 . And the list of indicators actually included in the 2019 SDG Index is available in Appendix 4 or more completely as Table 7 here: https://s3.amazonaws.com/sustainabledevelopment.report/2019/2019_sustainable_development_report.pdf

Table 7 Summary of SDGs, targets, and number of indicators used in the SDG Index

SDG	TITLE	DESCRIPTION	TARGETS	SDG-I
1	No Poverty	End poverty in all its forms everywhere	7	3
2	Zero Hunger	End hunger achieve food security and improved nutrition and promote sustainable agriculture	8	8
3	Good Health & wellbeing	Ensure healthy lives and promote well-being for all at all ages	13	17
4	Quality Education	Ensure inclusive and quality education for all and promote lifelong learning	10	9
5	Gender Equality	Achieve gender equality and empower all women and girls	9	6
6	Clean Water & Sanitation	Ensure access to water & sanitation for all	8	7
7	Affordable & Clean Energy	Ensure access to affordable, reliable, sustainable and modern energy for all	5	4
8	Decent Work & Economic Growth	Promote inclusive and sustainable economic growth, employment and decent work for all	12	7
9	Industry, Innovation, and Infrastructure	Build resilient infrastructure, promote sustainable industrialization and foster innovation	8	10
10	Reduced Inequalities	Reduce inequality within and among countries	10	3
11	Sustainable Cities and Communities	Make cities inclusive, safe, resilient and sustainable	10	4
12	Responsible Consumption and Production	Ensure sustainable consumption and production patterns	11	7
13	Climate Action	Take urgent action to combat climate change and its impacts	5	5
14	Life Below Water	Conserve and sustainably use the oceans, seas and marine resources	10	4
15	Life on Land	Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss	12	5
16	Peace, Justice and Strong Institutions	Promote just, peaceful and inclusive societies	12	10
17	Partnerships for the Goals	Revitalize the global partnership for sustainable development	19	5

The clear intention behind the 2030 Agenda is that sustainable development is pursued across multiple fronts simultaneously. An alternative strategy entails prioritizing key goals and pursuing them sequentially, though this is a clear violation of holistic intention behind the 2030 Agenda. The SDG Open Working Group was clear and deliberate in its decision not to prioritize individual goals (Caballero 2019). A siloed approach would undermine the Agenda and lead to policy incoherence.

Silo-prevention is easiest if strategic complementarities, synergies, and trade-offs within and between goals and indicators can be identified and exploited. Breuer et al (2019) review the literature on attempts to organize and classify links between SDGs. One approach entails clustering goals and organizing them within a conceptual framework such as planetary boundaries (Rockstrom et al. 2009; O'Neill et al. 2018; Breuer et al. 2019). But these approaches organize goals around their stated intent, using the text and policy area as guides. They do not entail empirical analysis of the indicators themselves.

An alternative strategy arbitrarily places one goal at the centre of the analysis and examines its links to the rest of the SDGs. Singh et al (2018) develop a hierarchical structure for identifying links between SDG 14 (life below water) and the rest of the goals. Through a series of expert workshops, they identify 260 positive and just 7 negative relationships between SDG 14 indicators and the rest of the goals, but there is no statistical analysis of primary SDG data to support the findings. Others place specific issues at the centre of analysis and evaluate trade-offs across the goals. Canavan et al (2016) and Kanter et al (2018) focus on agriculture and nutrition, noting that policies to improve these outcomes will have impacts and dependencies across many other goals and must be designed and implemented at multiple scales, bringing global goals to local decision making.

An alternative approach entails analysing the SDGs as a suite, considering all goals simultaneously. Mapping connections from 107 individual targets across 16 SDGs, Le Blanc (2015) showed that SDG 12 (sustainable consumption and production) and SDG 10 (reduced inequality) were core 'hubs,' binding the suite of SDGs in a tighter network. However, his approach defined network links in terms of textual overlap between the official descriptions of goals and targets. This is a low bar. Any goal or target that mentions the word 'inequality' is granted a network link in Le Blanc's analysis. Furthermore, textual analysis of SDG descriptions and targets does not necessarily map on to statistics actually measured in specific indicators.

Griggs et al (2014) attempt to define a set of 'equations' that represent links and trade-offs between goals, but in effect arrive at something closer to a description of relationships than meaningful equations. Even here, they are limited in their analysis to just 6 goals. What these approaches have in common is that they largely focus on the stated intentions and official text of the SDGs. Instead, the inductive approach taken here is purely empirical, focusing on relatively newly available data to determine whether core themes can be identified. Plotting Human Development Index (HDI) scores against Ecological Footprints, Wackernagel et al (2017) show that countries with strong performance in both the SDGs and the HDI also have high Ecological Footprints. The top 10 SDG performers are among the top 15 HDI performers and have per capita Ecological Footprints that exceed World

Biocapacity per capita by over 200%, suggesting that that the development side of the SDGs dominates the sustainability side. The present analysis adds to this discussion by deploying a different method to a similar question. Namely, I examine whether the broad goals and multiple indicators of the SDGs can be empirically described as a fundamentally new direction for development.

4.3. Methods

Principal components analysis (PCA) is a tool for reducing the dimensionality of data whilst retaining as much information as possible. Originally proposed by Pearson (1901) and developed by Hotelling (1933), it is used to summarize complex and nuanced multivariate data in a succinct and readily interpretable manner (Dunteman 1989). The objective is to replace p observed and correlated variables $(x_1, \dots, x_p)$ with a small number of newly constructed and uncorrelated variables $(y_1, \dots, y_p)$ that convey most of the information contained in the original x's (Bartholomew et al. 2008). The newly constructed y variables are called principal components and are constructed such that y_1 explains the greatest possible proportion of the total variance contained in the original x's, whilst y_2 explains the greatest possible proportion of the remaining variance and so on (Bartholomew et al. 2008). If the first one or two y's explain most of the total variance of the original x's, then the dimensionality of the original data can be reduced from p variables to just one or two principal components.

PCA may only be undertaken when there is sufficient meaningful correlation among the original variables to warrant the principal component representation. Several widely used tests exist for establishing the adequacy of data for undertaking PCA: computation of Bartlett's sphericity test (Bartlett 1950), scree plot analysis, and Kaiser-Meyer-Olkin (KMO) measures of sampling adequacy (Dziuban and Shirkey 1974).

Bartlett's sphericity essentially examines whether each successive eigenvalue is significantly different from the remaining eigenvalues (Jackson 1993). Conceptually, it identifies the point at which remaining principal components describe a spherical distribution of points (i.e. they have no coherent interpretation). The test computes a chi-square statistic with H_0 that the sample correlation matrix describes independent variables from a normal population. Rejecting H_0 indicates the data are fit for PCA (Dziuban and Shirkey 1974). The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy tests the appropriateness of each variable for inclusion and the group as a whole. It takes values between 0 and 1, with interpretation as follows (Dziuban and Shirkey 1974):

Table 8 Interpretation of Kaiser-Meyer-Olkin Measure of Sampling Adequacy

Score	Adequacy of Data for PCA
0.00 – 0.49	Unacceptable
0.50 – 0.59	Miserable
0.60 – 0.69	Mediocre
0.70 – 0.79	Middling
0.80 – 0.89	Meritorious
0.90 – 1.00	Marvellous

Following Cox (2005) the theory underlying principal components analysis can be described as follows: Let **x** = $(X_1, X_2, \dots, X_p)'$ be the original variables (SDG scores). Let **y** = $(Y_1, Y_2, \dots, Y_p)'$ denote the newly created variables. PCA transforms **x** to **y** such that:

i. $Y_j = a_{1j}X_1 + a_{2j}X_2 + \dots + a_{pj}X_p \qquad (j = 1, \dots, p)$
ii. $corr(Y_j, Y_k) = 0 \qquad (j \neq k)$
iii. The $Y_j's$ are ordered such that $var(Y_1) \geq var(Y_2) \geq \dots \geq var(Y_p)$

The newly created Y_1 is the first principal component, Y_2 is the second, and so on.

Let **x** have a mean vector $\boldsymbol{\mu}$ and a covariance matrix $\boldsymbol{\Sigma}$. Let $\boldsymbol{a}_j = (a_{1j}, \dots, a_{pj})'$. The principal components are

$$Y_j = \boldsymbol{a}_j'\mathbf{x}$$

The first principal component, Y_1, is found by choosing $\boldsymbol{a}_1$ such that Y_1 has the largest possible variance, subject to the constraint that $\boldsymbol{a}_1'\boldsymbol{a}_1 = 1$. The constraint rules out the degenerate case in which $var(Y_j) \to \infty$ and is similarly imposed on all components, $\boldsymbol{a}_\mathrm{j}'\boldsymbol{a}_\mathrm{j} = 1 \; (j = 1, \dots, p)$.

Now $var(Y_1) - var(\boldsymbol{a}_1'\mathbf{x}) = \boldsymbol{a}_1'\boldsymbol{\Sigma}\boldsymbol{a}_1 = V$. We maximize $var(Y_1)$ using a Lagrange multiplier, λ, and so consider

$$V = \boldsymbol{a}_1'\boldsymbol{\Sigma}\boldsymbol{a}_1 - \lambda(\boldsymbol{a}_1'\boldsymbol{a}_1 - 1)$$

Differentiating with respect to $\boldsymbol{a}_1$, and setting equal to **0** gives

$$\frac{\partial V}{\partial \boldsymbol{a}_1} = 2\boldsymbol{\Sigma}\boldsymbol{a}_1 - 2\lambda\boldsymbol{a}_1 = \mathbf{0}$$

Hence

$$(\boldsymbol{\Sigma} - \lambda\mathbf{I})\boldsymbol{a}_1 = \mathbf{0} \qquad \textbf{(1)}$$

The matrix $\boldsymbol{\Sigma} - \lambda\mathbf{I}$ must be singular (i.e. its determinant is zero) in order for Eq 1 to have a solution other than $\boldsymbol{a}_1 = \mathbf{0}.$ Thus λ satisfies

$$|\boldsymbol{\Sigma} - \lambda\mathbf{I}| = \mathbf{0},$$

We there is a solution if and only if λ has an eigenvalue of $\boldsymbol{\Sigma}.$

Now $\mathbf{\Sigma}$ has p eigenvalues $\lambda_1, \lambda_2, \dots, \lambda_p$, which are all non-negative, since $\mathbf{\Sigma}$ is positive semi-definite. Assume these are distinct, and labelled such that $\lambda_1 > \lambda_2 > \cdots > \lambda_p \geq 0$. Now

$$\begin{aligned} var(Y_1) = var(\boldsymbol{a}_1'\mathbf{x}) = {} & \boldsymbol{a}_1'\mathbf{\Sigma}\boldsymbol{a}_1 \\ = {} & \boldsymbol{a}_1'\boldsymbol{\lambda}\mathbf{I}\boldsymbol{a}_1 \quad \text{(from Eq 1)} \\ = {} & \lambda\boldsymbol{a}_1'\boldsymbol{a}_1 \\ = {} & \lambda \end{aligned}$$

Since $var(Y_1)$ is to have maximum variance, λ has to be chosen as the largest eigenvalue, λ_1, and hence $\boldsymbol{a}_1$ must be the right eigenvector of $\mathbf{\Sigma}$ corresponding to λ_1.

The second principal component, Y_2, is found similarly. We have $Y_2 = \boldsymbol{a}_2'\mathbf{x}$ with the normalising condition $\boldsymbol{a}_2'\boldsymbol{a}_2 = 1$. We also need $cov(Y_1, Y_2) = 0$. Now

$$\begin{aligned} cov(Y_1, Y_2) = cov(\boldsymbol{a}_2'\mathbf{x}, \boldsymbol{a}_1'\mathbf{x}) \\ = {} & \mathrm{E}[\boldsymbol{a}_2'(\mathbf{x} - \boldsymbol{\mu}) \times \boldsymbol{a}_1'(\mathbf{x} - \boldsymbol{\mu})\,] \\ = {} & \mathrm{E}[\boldsymbol{a}_2'(\mathbf{x} - \boldsymbol{\mu})(\mathbf{x} - \boldsymbol{\mu})'\boldsymbol{a}_1] \\ = {} & \boldsymbol{a}_2'\mathrm{E}[(\mathbf{x} - \boldsymbol{\mu})(\mathbf{x} - \boldsymbol{\mu})']\boldsymbol{a}_1 \\ = {} & \boldsymbol{a}_2'\mathbf{\Sigma}\boldsymbol{a}_1 \\ = {} & \boldsymbol{a}_2'\boldsymbol{\lambda}_1\boldsymbol{a}_1 = \boldsymbol{\lambda}_1\boldsymbol{a}_2'\boldsymbol{a}_1 \\ = {} & 0, \text{ if and only if, } \boldsymbol{a}_2'\boldsymbol{a}_1 = 0 \end{aligned}$$

Thus $\boldsymbol{a}_1$ and $\boldsymbol{a}_2$ must be orthogonal.

We now maximise $var(Y_2)$ facing two constraints,

$$V = var(Y_2) = \boldsymbol{a}_2'\mathbf{\Sigma}\boldsymbol{a}_2 - \lambda(\boldsymbol{a}_2'\boldsymbol{a}_2 - 1) - \delta(\boldsymbol{a}_2'\boldsymbol{a}_1 - 0).$$

Differentiating with respect to $\boldsymbol{a}_2$ and equating to $\mathbf{0}$,

$$\frac{\partial V}{\partial \boldsymbol{a}_2} = 2(\mathbf{\Sigma} - \lambda\mathbf{I})\boldsymbol{a}_2 - \delta\boldsymbol{a}_1 = \mathbf{0} \qquad \text{Eq 2}$$

Premultiply by $\boldsymbol{a}_1'$, to give

$$2\boldsymbol{a}_1'(\mathbf{\Sigma} - \lambda\mathbf{I})\boldsymbol{a}_2 - \delta\boldsymbol{a}_1'\boldsymbol{a}_1 = \mathbf{0}$$

i.e.

$$2\boldsymbol{a}_1'\mathbf{\Sigma}\boldsymbol{a}_2 - 2\lambda\boldsymbol{a}_1'\boldsymbol{a}_2 - \delta\boldsymbol{a}_1'\boldsymbol{a}_1 = \mathbf{0} \qquad \text{Eq 3}$$

But $\boldsymbol{a}_1'\mathbf{\Sigma}\boldsymbol{a}_2 = cov(Y_1, Y_2) = 0$, $\boldsymbol{a}_1'\boldsymbol{a}_2 = 0$ and $\boldsymbol{a}_1'\boldsymbol{a}_1 = 1$, and thus Eq 3 reduces to

$$\delta = 0.$$

Hence, Eq 2 becomes

$$(\mathbf{\Sigma} - \lambda\mathbf{I})\boldsymbol{a}_2 = 0,$$

and

$$var(Y_2) \;=\; var(\boldsymbol{a}_2'\mathbf{x}) \;=\; \boldsymbol{a}_2'\boldsymbol{\Sigma}\boldsymbol{a}_2 \;=\; \boldsymbol{a}_2'\lambda\boldsymbol{a}_2 \;=\; \lambda.$$

This second λ also has an eigenvalue $\boldsymbol{\Sigma}$**.** It cannot be chosen as the largest eigenvalue (which is taken by the first principal component) and is instead chosen as the second largest eigenvalue so that $\boldsymbol{a}_2$ is the corresponding eigenvector. The process is continued to obtain the rest of the principal components $Y_1, Y_2, \dots, Y_p$. The jth component is given by $Y_j = \boldsymbol{a}_j'\mathbf{x}$, where $\boldsymbol{a}_\mathrm{j}$ is the jth eigenvector of $\boldsymbol{\Sigma}$, and $var(\mathrm{Y}_j) = \lambda_j$, where λ_j is the jth eigenvalue of $\boldsymbol{\Sigma}$.

Organising all principal components into a single vector, **y** = $(Y_1, Y_2, \dots, Y_p)'$, we place the eigenvectors of $\boldsymbol{\Sigma}$ into matrix $\mathbf{A}$, so that $\mathbf{A} = [\,\boldsymbol{a}_1\,,\ \boldsymbol{a}_2\,,\ \dots\ ,\ \boldsymbol{a}_\mathrm{j}]$. Then

$$\mathbf{y} = \mathbf{A'x}$$

with

$$var(\mathbf{y}) = \boldsymbol{\Lambda} = diag(\lambda_1, \lambda_2, \dots, \lambda_p)$$

Now

$$var(\mathbf{y}) = \boldsymbol{\Lambda} = \mathbf{A}'\boldsymbol{\Sigma}\mathbf{A},$$

and so, as $\mathbf{A}$ is orthogonal with $\mathbf{A^{-1}} = \mathbf{A}'$**,**

$$\boldsymbol{\Sigma} = \mathbf{A}\boldsymbol{\Lambda}\mathbf{A}',$$

Showing that finding principal components is essentially the same as finding the spectral decomposition of $\boldsymbol{\Sigma}$.

Now

$$\begin{aligned}\sum_{j=1}^{p} var(Y_j) = \sum_{j=1}^{p} \lambda_j &= \mathrm{tr}(\boldsymbol{\Lambda}) \\ &= \mathrm{tr}(\mathbf{A}'\boldsymbol{\Sigma}\mathbf{A}) \\ &= \mathrm{tr}(\boldsymbol{\Sigma}\mathbf{A}'\mathbf{A}) \\ &= \mathrm{tr}(\boldsymbol{\Sigma})\end{aligned}$$

Therefore

$$\sum_{j=1}^{p} var(Y_j) = \sum_{j=1}^{p} var(X_j)$$

and so the sum of the variances of the principal components is equal to the sum of the variances of the original variables. $\sum_{j=1}^{p} var(X_j)$ is the total variation in the data, and that the jth principal component accounts for the proportion

$$\frac{\lambda_j}{\sum_{i=1}^{p} \lambda_i}$$

of this. Similarly, the first m principal components account for

$$\frac{\sum_{i=1}^{m} \lambda_i}{\sum_{i=1}^{p} \lambda_i}$$

Of the total variation.

Principal components analysis is a powerful tool for distilling salient features from complex data. It is widely used through the ecology, biology, psychology, pedagogy, business management, and market research. However, it is rarely used in economics, despite many concepts and datasets that are strong candidates for this kind of analysis. Business and consumer confidence are broadly acknowledged as important economic indicators yet can only be understood as latent concepts. Indeed, many of the most interesting areas of contemporary economic research deal specifically with latent variables such as social capital (Scrivens and Smith 2013; Wealth Economy 2019), identity (Akerlof and Kranton 2000, 2010), and economic narratives (Shiller 2017, 2019). It is particularly useful for analysing survey data. Using survey responses from 12 developed and developing countries, Bain et al (2019) use PCA to construct mental maps describing public perceptions of the sustainable development goals. Results showed that the public understanding of sustainability differs across countries and cultures, and can therefore be used in targeting communications about sustainable development. Bain et al (2019) use PCA to analyse survey responses and comment on the public understanding of sustainability. In contrast, I analyse data on SDG performance directly to comment on whether the SDG framework in practice is delivering on its objectives in principal.

4.4. Data

The 2030 Agenda for Sustainable Development sets out 17 Sustainable Development Goals that include 169 targets measured by 232 unique indicators. The development of new official statistics and economic measures for setting and evaluating policy is an important element of the 2030 Agenda. While some of the 232 SDG indicators have close analogues in existing official statistics, many do not. This is by design. One objective of the SDGs is to provide a broader focus for policy and measurement, going beyond standard income-driven measures. A consequence, however, is that there is no comprehensive dataset with global coverage that includes all 232 indicators. This too, is by design. Whilst the broad goals and targets are set, the statistical standards are ‘living’ in that they continue to evolve as data becomes available and lessons are learned during implementation.

In the absence of an official UN dataset with comprehensive SDG coverage, data for this study come from the SDG Index and Dashboards 2019 (Sachs et al. 2019). Developed by Bertelsmann Stiftung and the Sustainable Development Solutions Network, the SDG Index measures country-level performance on each of the 17 SDGs. It is not an official UN Standard, but is audited by the European Commission Joint Research Centre (Papadimitriou et al. 2019). The 2019 Index covers 162 countries and includes a total 114 indicators, 85 of which have global coverage with an additional 29 for OECD countries. Approximately 35% of these are exact matches for the indicators approved by the Inter-Agency and Expert Group on SDG Indicators, 24% are closely aligned, and 40% are not available in UNSTATS. Criteria for inclusion in the Index include:

1. Global relevance, applicability across countries, and international comparability
2. Statistical adequacy
3. Regular, timely availability of data
4. Data quality and the legitimacy and reliability of the data source
5. Global coverage (data must be available for at least 80% of UN Member States with population greater than 1 million).

The underlying data for the 2019 Index entails a mix of official (≈ 65%) and non-official (≈ 35%) data. More than half of the official data comes from OECD, WHO, and UNICEF. Non-official data come from academic institutions, NGOs, and the published research literature. They are used where official measures are known to contain systematic biases and to bridge data gaps, "in particular to gauge environmental spill over effects embodied into trade via input-output estimations" (Lafortune et al. 2018, p15). On average, 7 indicators per goal are included, though this varies from 3 indicators for SDG 1 (zero poverty) and SDG 10 (reduced inequality), to 17 indicators for SDG 3 (good health and wellbeing). See Sachs et al (2019) for a full mapping of 114 indicators across the 17 goals.

Indicator data is normalized via the min-max method with a rescaling range of [0, 100]. This facilitates interpretation as higher scores indicate better performance (Lafortune et al. 2018; Papadimitriou et al. 2019). The SDG Index is constructed such that a country's score on each goal can be interpreted as the percentage of achievement. For instance, the UK's score on SDG 5 (gender equality) is 81.29 indicating that the UK is on average 81.29% of the way to achieving this goal. As such, country scores for each goal can range from 0 (worst possible position) to 100 (best possible position). This requires a definition of the best and worst possible positions. Where possible, absolute quantitative thresholds are used (e.g. zero poverty, universal school completion, etc). Where no quantitative target is available, the upper bound is determined according to the 'leave no one behind' principle. In practice, this amounts to using universal access as the upper bound for some topics (e.g. coverage of public services, access to infrastructure, wastewater treatment, etc) or ‘zero deprivation’ (e.g. for measures of extreme poverty such as wasting). Deadline-specific biophysical targets such as ‘zero GHG emissions from electricity by 2070’ are set as their own upper bounds. In some cases, several countries already out-perform the SDG target (e.g. child mortality rates). In such instances, the upper bound is set as the average of the top five performing countries. Overall, just 12% of indicator used in the Index have upper bounds that exactly match official SDG targets. 44% are set using the average of top performers, 26% employ biophysical maximums, and 19% rely on the leave no one behind principle (Lafortune et al. 2018).

Several caveats must be considered when using the SDG Index. Not all goals have equal country coverage (see Table 7), and not all countries have equal SDG coverage. It is possible that (i) an individual indicator has sufficient global coverage for inclusion in the Index whilst (ii) a given country lacks data on that specific indicator. In such cases, countries with missing data are assigned their regional average score for each goal. For instance, Afghanistan did not have data for SDG 1 and was therefore assigned the regional score for East Europe and Central Asia (Papadimitriou et al. 2019). Additionally, while the SDG Index assigns equal weights at the goal level, this does not mean that it assigns equal weights at the indicator level. For instance, each of the 17 indicators used to calculate the Index score for SDG 3 contribute 1/17th of the weight, whereas the 3 indicators used to calculate the score for SDG 1 contribute 1/3rd.

To aggregate from individual indicators to scores for each SDG, the Index relies simply on the arithmetic mean. This aids interpretation, but enables perfect compensability between indicators. Within a given goal, high scores on some indicators can ‘compensate’ for low scores on another. This is an undesirable feature. One alternative is to aggregate from the indicator level to the goal level using the geometric mean, as this is a non-compensatory measure (meaning success in one indicator cannot compensate poor performance in another). Papadimitriou et al (2019) show that this has minimal effect on actual rankings. The European Commission’s statistical audit concludes that the Index results are “robust enough, allowing meaningful conclusions to be drawn from the index” (Papadimitriou et al. 2019, p2).

Table 9 provides summary statistics of country-level SDG Index scores for the 2019 Index. Sample sizes differ slightly across goals due to data availability. For instance, SDG 14 (life below water) has no data for land-locked countries. Variances range an order of magnitude, from 95.75 (SDG 2 – zero hunger) to 991.94 (SDG 1 – no poverty). This is important in PCA because components are constructed to explain the greatest possible share of total variance across the original variables. Original variables with greater variance are therefore weighted more heavily. If the original variables are recorded in different scales, this could lead to arbitrary and undue influence on the PCA. To avoid this arbitrary weighting, the correlation matrix is analysed rather than the covariance matrix (Bartholomew et al. 2008; Jollife and Cadima 2016).

The data is fully appropriate for the application of PCA methods. Bartlett's test of sphericity returns a Chi-square statistic of 1605.159 with 136 degrees of freedom. The null (that the original variables are insufficiently correlated for PCA) is rejected with p-value 0.000. Similarly, the Kaiser-Meyer-Olkin measure of sampling adequacy KMO = 0.901, which is "marvellous" (Dziuban and Shirkey 1974).

Table 9 Summary Statistics of SDG Index Scores

	N	Mean	St.Dev	variance	min	max
SDG 1	151.00	74.40	31.50	991.94	0.00	100.00
SDG 2	162.00	53.56	9.79	95.75	19.01	77.87
SDG 3	162.00	70.04	20.11	404.57	17.59	97.89
SDG 4	162.00	76.90	23.37	546.05	8.42	99.92
SDG 5	162.00	60.17	16.19	262.16	10.39	89.24
SDG 6	162.00	67.64	16.44	270.15	27.47	96.98
SDG 7	162.00	71.13	28.14	791.85	0.00	99.37
SDG 8	162.00	71.63	10.43	108.72	36.48	90.61
SDG 9	162.00	35.06	23.72	562.67	1.87	93.31
SDG 10	148.00	59.12	24.36	593.27	0.00	100.00
SDG 11	162.00	71.81	16.10	259.26	27.76	98.35
SDG 12	162.00	77.43	19.00	360.92	22.17	99.29
SDG 13	162.00	86.61	13.35	178.35	33.41	99.43
SDG 14	126.00	50.51	15.05	226.37	8.67	81.30
SDG 15	162.00	64.81	14.64	214.37	23.50	93.31
SDG 16	162.00	66.01	14.05	197.52	31.07	93.05
SDG 17	162.00	64.46	14.79	218.84	27.24	100.00

Table 10 presents the correlation matrix across all SDG Index scores. Correlations are generally strong and positive, indicating a degree of overall coherence among the SDG Index scores and that the data are appropriate for PCA. Correlations with absolute value less than 0.2 are in grey while strong negative correlations are highlighted in red. Goals 1-11 and 16 deal with poverty, hunger, health, education, gender equality, clean water, energy, growth, innovation, inequality and communities and peace and justice. With some apology for generality, these are the 'quality of life' goals. Goals 12-15 deal with production and consumption patterns, climate change, oceans, and terrestrial ecosystems. They are the 'environmental impact' goals. Table 10 suggests a trade-off between quality of life and environmental impact, similar in nature to that found by Wackernagel et al (2017).

Table 10 Correlation Matrix of SDG Index Scores

	SDG1	SDG2	SDG3	SDG4	SDG5	SDG6	SDG7	SDG8	SDG9	SDG10	SDG11	SDG12	SDG13	SDG14	SDG15	SDG16	SDG17
SDG1	1																
SDG2	0.5446	1															
SDG3	0.8559	0.6194	1														
SDG4	0.7838	0.6382	0.8425	1													
SDG5	0.4531	0.5202	0.633	0.6078	1												
SDG6	0.7704	0.674	0.8644	0.7894	0.6593	1											
SDG7	0.8615	0.5144	0.86	0.8106	0.5617	0.7776	1										
SDG8	0.5322	0.6286	0.6859	0.645	0.5794	0.6619	0.5292	1									
SDG9	0.6819	0.6946	0.8222	0.6924	0.6684	0.7844	0.7144	0.6853	1								
SDG10	0.3058	0.3241	0.3385	0.1606	0.062	0.2357	0.1357	0.194	0.395	1							
SDG11	0.6606	0.4401	0.7772	0.7309	0.6615	0.7029	0.6641	0.5795	0.5881	0.1176	1						
SDG12	-0.627	-0.5623	-0.8059	-0.6468	-0.6328	-0.766	-0.6542	-0.5947	-0.8758	-0.3675	-0.5882	1					
SDG13	-0.3588	-0.1055	-0.4089	-0.3537	-0.3055	-0.3967	-0.2956	-0.2012	-0.4203	-0.2099	-0.3465	0.5457	1				
SDG14	-0.128	0.0479	-0.0895	-0.0677	0.1322	0.0153	-0.0855	0.0719	-0.0376	-0.1831	-0.0194	0.0318	0.0087	1			
SDG15	0.0305	0.2839	0.0962	0.0779	0.1946	0.1506	0.1058	0.1719	0.2177	0.0457	-0.0194	-0.1964	0.1261	0.2124	1		
SDG16	0.6654	0.5614	0.7856	0.6674	0.5102	0.6641	0.5918	0.6008	0.7678	0.4603	0.6864	-0.7228	-0.4305	-0.0776	0.1242	1	
SDG17	0.2205	0.0898	0.2483	0.1907	0.1613	0.2155	0.3233	-0.0609	0.1831	0.1006	0.2197	-0.1302	-0.207	-0.0784	-0.053	0.1926	1

Table 10 presents the correlation matrix across all goals included in the PCA. Correlations with absolute magnitude < 0.2 are in grey. Strong negative correlations are highlighted in red. Overall SDG Index scores are strongly correlated. SDG 12 & 13 have strong negative correlations with the rest of the set. SDG 14 & 15, and to a lesser extent SDG 17 are poorly correlated with the rest of the set.

4.5. Results

Table 11 shows the main results from the PCA on all 17 SDG Index scores. Columns 1-2 list the components and their Eigenvalues, while column 3 indicates the share of total original variance captured by each component. Column 4 shows the cumulative share of variance explained when all preceding components are combined. Results clearly indicate a dominant first component capturing 52% of the variation across all 17 SDG Index scores. In total, four components have Eigenvalues greater than one and explain a cumulative 74.44 % of total variance.

Table 11 Variance explained by each principal component

Component	Variance Explained		
	Variance Eigenvalue	%	Cumulative %
1	8.8403	0.5200	0.5200
2	1.5560	0.0915	0.6115
3	1.2372	0.0728	0.6843
4	1.0213	0.0601	0.7444
5	0.9554	0.0562	0.8006
6	0.6651	0.0391	0.8397
7	0.5820	0.0342	0.8740
8	0.4653	0.0274	0.9013
9	0.3651	0.0215	0.9228
10	0.3201	0.0188	0.9416
11	0.2715	0.0160	0.9576
12	0.2054	0.0121	0.9697
13	0.1618	0.0095	0.9792
14	0.1334	0.0078	0.9870
15	0.0873	0.0051	0.9922
16	0.0767	0.0045	0.9967
17	0.0561	0.0033	1.0000

Table 11. Variance explained by each component. N = 110. 4 components have Eigenvalues > 1.00, $\rho = 0.7444$. Eigenvalues are the variances of each principal component.

A promax rotation[6] is applied to facilitate interpretation of components. Promax rotations allow correlation between components (i.e. they relax the standard orthogonality restriction). This is acceptable if (i) some correlation between the latent concepts that the PCA is trying to uncover is expected and (ii) interpretation is improved. Both requirements are met. We would expect overlap between components if the SDGs they are trying to describe are part of a coherent, integrated framework. The resulting rotated components lend themselves to an interpretation that is at least

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[6] Component rotations are commonly used to aid model interpretation. Promax rotations permit some correlation between components, which is justified here because we would expect some correlation between SDGs (Bartholomew et al. 2008).

credible. However, for completeness, the full set of unrotated loadings across all 17 components is presented in Appendix 5.

Table 12 reports loadings for the first four rotated components (Eigenvalues > 1). The last row indicates the proportion of total original variance explained by each component. These differ slightly from the unrotated explained variance reported in Table 11 and Appendix 5. This is a side-effect of promax rotation. In combination, the four components still describe 74.44% of the total original variation (though the sum across the final row is 75.43, this overstates the model's explanatory power because some of the components are explaining some of the same original variation). Rho is still 0.7444 after promax rotation. Loadings with absolute value less than 0.2000 are suppressed in the output.

Table 12 Component loadings for the four component model

VARIABLE	COMP1	COMP2	COMP3	COMP4	UNEXPLAINED
SDG1	0.3291			-0.2334	0.2100
SDG2	0.2347		0.2691		0.3045
SDG3	0.3288				0.0739
SDG4	0.3678				0.1665
SDG5	0.2530			0.3100	0.3261
SDG6	0.3148				0.1668
SDG7	0.3672				0.1818
SDG8	0.2766		0.2293		0.3205
SDG9	0.2232	0.2312			0.1416
SDG10		0.8091		-0.2473	0.1839
SDG11	0.3303	-0.2142			0.2695
SDG12		-0.2468	0.2085		0.1846
SDG13		-0.2078	0.7213		0.2441
SDG14		-0.2851		0.8050	0.2645
SDG15			0.2584	0.4219	0.4501
SDG16	0.1912	0.2886			0.2455
SDG17			-0.4725		0.6114
% OF TOTAL VARIANCE	**47.37**	**10.21**	**8.94**	**8.91**	

Table 12. Promax rotation of component loadings for the first four components (Eigenvalues > 1). N = 110 and ρ = 0.7444.

The loadings on the first component are generally positive and of similar magnitude[7]. This component could be interpreted as overall development. Countries with high SDG Index scores for these Goals will score highly on this component. The second component contrasts countries that score well on SDG 10 (reduced inequality) and SDG 16 (peace, justice, and strong institutions) against those that are performing well in reducing their environmental impacts (SDG 12 deals with material footprints,

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[7] Loadings for SDG 10, 12, 14, and 15 are negative, but with small absolute value.

SDG13 with GHG emissions, SDG14 with impact on oceans). Countries with a high score on this component are achieving greater progress towards SDG 10 and 16, with relatively less progress towards reducing environmental impact and natural capital depletions.

Table 13 Interpretation of principal components (four component model)

Component	*Explained Variance*	*Interpretation*
1	47.37 %	Overall development
2	10.21 %	Contrasting social capital against natural capital
3	8.94 %	Uninterpreted
4	8.91 %	Contrasting ecosystem management against poverty and inequality

Table 13. Offers interpretation of the four principal components with Eigenvalues greater than 1, with the aid of promax rotation. In combination, they explain 74.44% of the total original variance. All 17 SDGs are included.

The third component appears to contrast SDG 13 against SDG 17 but should not be over interpreted. The unexplained variance for SDG 17 is 61% and the goal is an outlier in terms of its targets, indicators, and coverage in the SDG Index. To make strong claims would be imprudent and the responsible course of action is to avoid ‘imposing’ and interpretation on it (see chapter 4.7). The fourth component, accounting for 8.91% of total variation contrasts SDG 14-15 (life below water and life on land) against SDG 1 (zero poverty) and SDG 10 (reduced inequality). In summary, the first four components can be interpreted as described in Table 13.

Figure 13 maps country scores on the first two components. Colours refer to income level. The first component, named ‘overall development’ generates clearly ordered groupings by income category. High (low) income countries have high (low) scores on this component. SDGs 10 and 16 deal with inequality, peace, justice and strong institutions. Combined, and with some generosity, these can be interpreted as reflecting some variant of social capital. SDGs 12-14, and to a lesser extent 11, can be said to reflect natural capital. SDG 12’s indicators include solid waste, SO_2 emissions, and nitrogen footprints. SDG 13 includes various measures of GHG emissions. SDG 14 includes marine protected areas and measures of overfishing. Thus, the second principal component contrasts performance in social versus natural capital oriented SDGs.

Figure 14 plots country scores on components 2 and 3, colour-coded by income category as above. The lack of clearly identifiable clusters of colour demonstrates that these components cannot be described by income level and truly capture different dimensions of sustainability.

Figure 13 Country-level scores on the first two principal components

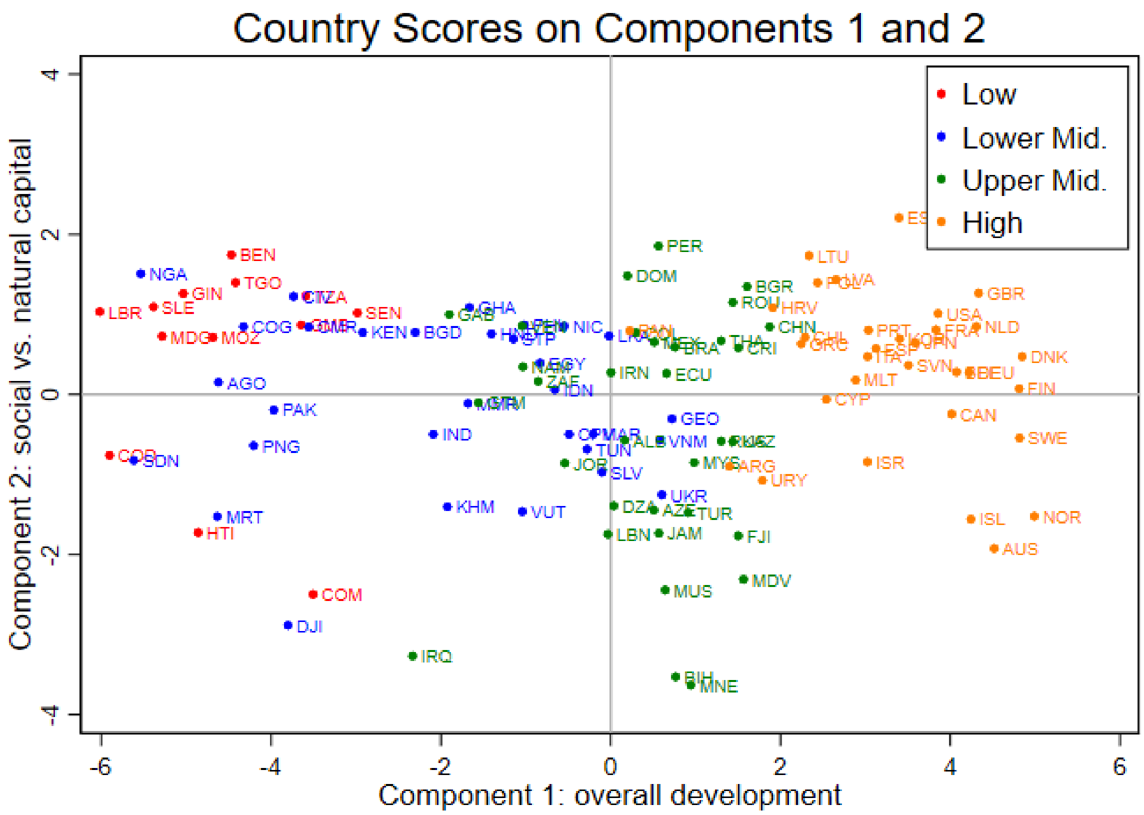
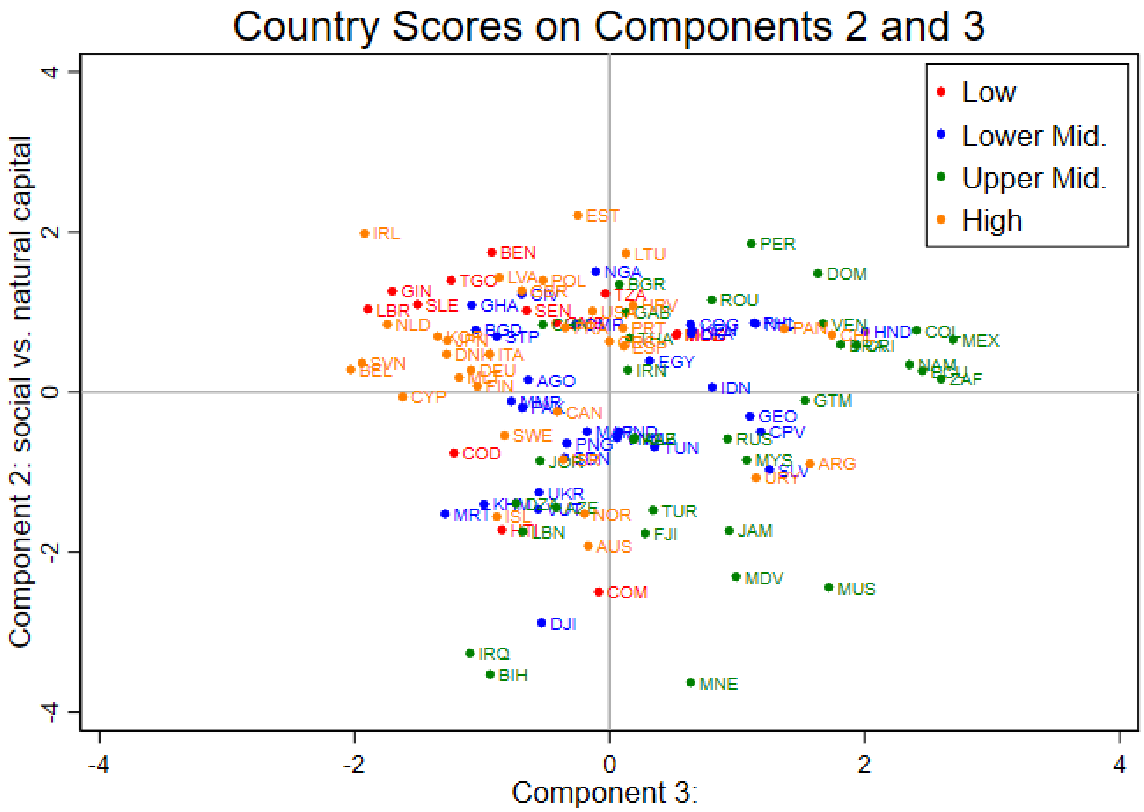


Figure 14 Country scores on components 2 and 3



4.6. Discussion

The sustainable development goals provide the organizing framework and direction to which the international development community is committed. They rightly recognize that sustainable development is a broad concept with constituent elements that range from the clearly complementary to the seemingly contradictory. The breadth of scope means that measuring progress requires a wide range of data, some already covered in official statistics, some not. The process of defining and collecting progress indicators is ongoing, but adoption and (at least partial) implementation of the SDGs is already under way. To support coherent policy, it is helpful to identify potential synergies and trade-offs, and to have some method of measuring what works. At this early stage, and before they undergo their first major revision, it is also useful to assess whether progress towards the goals – as measured by SDG indicators – affirms and reinforces what we already know about sustainable development and delivers on the intent of the 2030 agenda. That is, does it pass the 'sniff test'? Some simplification of the myriad goals and indicators is needed.

Principal components analysis is an established methodology for reducing the dimensionality of complex correlated data and can provide useful insights into these issues. Preliminary analysis (KMO, Bartlett's sphericity, scree plot examination) on data from the SDG Index confirms that this data is appropriate for PCA.

Examination of the correlation matrix (Table 10) indicates that amidst strong overall agreement among goals, there is an important break. 'Quality of life' goals (SDGs 1-9 and 16) are strongly correlated with each other, and strongly negatively correlated with 'environmental impact' goals (SDG 12-13, and to a lesser extent SDG 14-15). This underscores one of this paper's main motivations: assessing whether measured progress in SDG performance actually delivers for people, planet, and prosperity or whether there are unavoidable trade-offs between environmental and economic outcomes.

Table 11 shows the proportion of original variance described by each principal component, with the cumulative tally in the final column. Four components are needed to describe 74.44% of original variance. The large proportion of variance explained by the first principal component (52%) suggests a dominant common feature across most of the goals. The loadings of each SDG onto each component (shown after promax rotation in Table 11) can be interpreted as the weight given to each variable on each component. The first component (Table 11, column 2) has positive loadings fairly evenly distributed across most of the goals. Negative loadings on component 1 are found for SDG 10, 12, 14, and 15. Because these are all less than 0.1 in absolute value, they do not weigh heavily on the component. In combination, the pattern and distribution of SDGs loading onto the first principal component lend a clear interpretation: this is a broad measure of overall development in the traditional sense.

Figure 13 plots individual country scores on the first two principal components. The first two PCs account for 52% and 9.15% of total variation in the SDG Index. Thus, the two-dimensional scatter-plot of country scores in Figure 13 represents a moderate to good approximation to the original scatter-plot in 17-dimensional space. It is, by definition, "the best variance-preserving two-dimensional plot of the data", representing over 61% of total variation. Component 1 (overall development) is on the horizontal axis. Colours distinguish between low, lower middle, upper middle, and high income countries as classified by the United Nations. The distribution of countries from left to right by income status lends further support to the interpretation of component 1 as 'overall development'. Finally, Table 14 reports Pearson correlation coefficients between component scores and per capita GDP. The very strong positive correlation between per capita GDP and PC 1 confirms statistically what Figure 13 conveys graphically: that income remains a major determinant of SDG performance.

Table 14 Correlation between per capita GDP and the principal components

	GDP PER CAPITA	PC1	PC2	PC3	PC4
GDP PER CAPITA	1				
PC1 'OVERALL DEVELOPMENT'	0.858	1			
PC1 'NATURAL VS SOCIAL CAPITAL'	0.0574	-0.026	1		
PC3 UNINTERPRETED	-0.2303	-0.0007	-0.0203	1	
PC4 ECOSYSTEMS VS POVERTY	-0.1745	0.0018	0.0065	0.0045	1

*GDP per capita in 2017 PPP. Table show Pearson's correlation coefficients between each principal component and per capita GDP.

That this component describes the majority of original variance indicates that overall development level is still the majority focus of the SDGs, *if* we use available SDG indicators as the basis for measurement. But it is a small majority, at just 52% of variation explained. That 48% of the variance is not explained by overall development is a clear signal that SDG performance cannot meaningfully be proxied by per capita income. Doing so would ignore 48% of the variation in SDG scores.

PC 2 describes a different dimension of sustainable development. Capturing the maximum possible remaining variation that is not already described by PC1, PC2 contrasts a very strong positive loading from SDG 10 (reduced inequality) and moderate positive loadings from SDG 9 (industry, innovation, and manufacturing) and SDG 16 (peace, justice and strong institutions) against moderate negative loadings from SDGs 11-14 (sustainable cities, responsible consumption and production, climate action, and life below water).

Indicators for SDG 9 include internet coverage, mobile phone access, percentage of women in science and engineering and university performance (Sachs et al. 2019). SDG 10 indicators focus on income inequality – the Gini Index, Palma ratio (income share of the top 10% divided by the income share of the bottom 40%), and the elderly poverty rate. And SDG 16 indicators include data on crime rates, prison population, corruption indices, and freedom of the press. Together, these can be considered the ‘social capital goals’. With these groupings, PC2 can be interpreted as contrasting social capital performance against natural capital performance. Countries with high scores on this component are closer to achieving SDGs 10 and 16 than they are to achieving goals 11-14.

Similarly, PC 3 contrasts a strong positive loading from SDG 13 (climate action) against a strong negative loading from SDG 17 (partnerships for the goals). For reasons outlined below (Chapter 4.7), this should not be over interpreted. PC 4 has very strong positive loadings for SDG 14-15 (life below water and life on land) and moderate negative loadings from SDG 10 (inequality) and SDG 1 (no poverty). This is interpreted in Table 13 as contrasting ecosystem management against poverty and inequality.

Restricting the model to just four components means that some of the variation in the original variables (SDGs) is unexplained. The final column of Table 12 reports the variation in each SDG that cannot be explained by the four components[8]. Some SDGs are better explained by the model than others. For instance, the four-component model explains (1 - 0.0739) 93% of variation in SDG 3, but only 39% of variation in SDG 17. Because SDG 17 (i) loads heavily onto PC 3 and (ii) is so poorly explained by the four-component model, PC 3 may not have meaningful interpretation.

Several ‘stopping rules’ have been proposed to identify the ‘correct’ number of components to include in a PCA (Jackson 1993; Peres-Neto et al. 2005). In practice, it is more an art than a science. PCA is technique for reducing dimensionality and making sense of large complex data. One school of thought is that the right number of components to include is determined by how well they distil interesting information from a larger dataset (Bartholomew et al. 2008). A general rule of thumb is that components with eigenvalues greater than one should be retained. The eigenvalue of PC 4 is 1.0213, explaining 6% of total variation, while the eigenvalue for PC 5 is 0.9554, explaining 5.6% of total variation (Table 11). It is a narrow distinction, but if the 17 original variables (SDGs) were perfectly

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[8] Note that in the unrestricted model in Appendix 5, unexplained variation is 0 for all variables (SDGs)

uncorrelated, each could be expected to describe 1/17th (5.88%) of total variance. Components that describe less than this would carry less information than the original variables.

4.7. Robustness

SDG 17 (partnerships for the goals) is an outlier. It is weakly correlated with the rest of the goals (Table 10), it has by far the largest number of targets (Table 7), though only 5 indicators are actually included in the SDG Index (Lafortune et al. 2018), and these have highly uneven coverage (Papadimitriou et al. 2019). Two robustness tests are performed. First, a 5-component model is calculated to determine whether the Kaiser rule of thumb that only components with eigenvalues greater than one must be retained is too restrictive. The four-component model failed to describe over 60% of the variation in SDG 17, and the eigenvalue for the 5th component was very close to one at 0.9554. Including a 5th component therefore could aid interpretation of PC 3. Moreover, if the loadings on PC 1-2 in the five-component model are consistent with those in the four-component model, this offers further confidence in their interpretation.

Table 15 Component loadings for the 5-component model

VARIABLE	COMP1	COMP2	COMP3	COMP4	COMP5	UNEXPLAINED
SDG1	0.3269		-0.2089			0.2073
SDG2	0.2372			0.2757		0.2878
SDG3	0.3279					0.0739
SDG4	0.3665					0.1662
SDG5	0.2524		0.2713			0.3243
SDG6	0.3139					0.1666
SDG7	0.3614				0.2089	0.1491
SDG8	0.2834				-0.3444	0.2600
SDG9	0.2252	0.2179				0.1416
SDG10		0.7828	-0.1686*			0.1786
SDG11	0.3287	-0.2223				0.2558
SDG12		-0.2165		0.2496		0.1738
SDG13		-0.1482*		0.7696		0.1632
SDG14		-0.2877	0.7315			0.2638
SDG15			0.5476	0.4021		0.2429
SDG16		0.2657				0.2424
SDG17					0.8968	0.0925
% OF TOTAL VARIANCE	**47.31**	**9.27**	**8.40**	**8.12**	**6.69**	

Table 15. Promax rotation of component loadings for five components. N = 110 and ρ = 0.8006. Loadings with absolute value less than 0.2 are suppressed or (*) shown in grey for comparison with Table 12.

Table 15 presents loadings for the 5-component model. PC 1 and PC 2 have similar loadings to the 4-component model, explain about the same share of total variance, and their interpretation does not change. But the third component does change. PC 3 in the five-component model (PC3_5) no longer contrasts SDG 13 against SDG 17 (as in the four-component model PC3_4). In the five-component model, PC3_5 now contrasts high positive loadings for SDG 14-15 against moderate negative loadings from SDG 1. This is similar in interpretation to the fourth principal component in the 4-component model. Results across the two models reinforce the interpretation of three principal components that can be considered, overall development, contrasting social versus natural capital related performance, and contrasting ecosystem management against poverty.

The five component model explains 80% of total variance, while the more restricted four-component model described 74.44%. However, the unexplained variation in the five-component model is more evenly distributed across the goals. Notably, the unexplained variation in SDG 17 falls from 61% in the four-component model to 9.25% in the five-component model. PC4_5 has strong positive loadings from SDG 13 (climate action) and moderate positive loadings from SDG 15, 12, and 2. Finally, PC 5 contrasts a very strong positive loading from SDG 17 against a moderate negative loading from SDG 8. This could be interpreted as distinguishing progress in partnerships for the goals against progress in decent work and economic growth.

Table 16 Component loadings across four components and 16 SDGs

VARIABLE	COMP1	COMP2	COMP3	COMP4	UNEXPLAINED
SDG1	0.3392		-0.2405		0.2053
SDG2	0.2219			0.2942	0.2810
SDG3	0.3332				0.0740
SDG4	0.3723				0.1650
SDG5	0.2493		0.3003		0.3244
SDG6	0.3162				0.1673
SDG7	0.3809				0.1856
SDG8	0.2582				0.3718
SDG9	0.2180	0.2269			0.1416
SDG10		0.7991	-0.2275		0.1771
SDG11	0.3364	-0.2254			0.2593
SDG12		-0.2245		0.2476	0.1745
SDG13				0.7819	0.1550
SDG14		-0.2801	0.7807		0.2627
SDG15			0.4348	0.3905	0.3170
SDG16		0.2743			0.2440
% OF VARIATION	**49.96**	**10.32**	**9.25**	**8.51**	

Table 16. Promax rotation of loadings for the first four components (Eigenvalues > 1). N = 110, ρ = 0.7809. Loadings with absolute value less than 0.2 are suppressed. SDG 17 is omitted from the analysis.

A second robustness check concedes that SDG 17 is an outlier and considers the principal components in a model with only the first 16 SDGs. Table 16 presents loadings from that model. The model describes a slightly higher proportion (ρ = 0.7809) of original variance than the 17-goal version described in Table 12 (ρ = 0.7444). Loadings and interpretation of PC 1 and PC 2 are relatively unchanged. PC 3 is similar to previous models, describing 9.25% of variation and contrasting high positive loadings from SDG 14-15 against moderate negative loadings from goals on poverty and inequality. This is similarly interpreted as distinguishing between progress on ecosystem management versus poverty and inequality goals.

4.8. Conclusion

Sustainable development is a multifaceted process with complex complementarities and myriad potential trade-offs. The Sustainable Development Goals were developed by the international community in recognition of the fact that the old development paradigm had not adequately accounted for its contribution and sensitivity to mounting environmental and social pressures. The general intent of the SDGs was to re-orient the global political economy to deliver more inclusive growth, protect environmental assets, and promote human wellbeing alongside material outcomes.

Progress towards the 17 goals is measured by a suite of indicators whose data varies from well-established to aspirational. The process of refining, adding and replacing indicators is on-going. This dynamic and not always straightforward process can make it difficult to identify strategic complementarities and policy trade-offs. Given such complexity, tools for distilling core components from large data can help demonstrate the extent to which the SDGs truly represent a departure from and alternative to standard measures of development such as per capita GDP.

Principal components analysis was applied to the most comprehensive global set of data on SDG Indicators, the SDG Index (Sachs et al. 2019). It revealed a single dominant principal component that explains 52% of variation across the goals and which can be interpreted as overall development level. Country scores on this component clearly show that per capita income remains a leading indicator of progress within the SDG framework. However, it also shows that 48% of variation cannot be described by per capita income, suggesting that nearly half of SDG progress relies on other, non-income components. A suite of analyses that varied the number of components and goals revealed a component describing about 10% of variation in SDG performance that contrasts performance on reducing inequality against performance on reducing environmental impacts. A third component describing 8.4 – 9.25 % of variation contrasts marine and terrestrial ecosystem conservation against poverty and inequality.

Results suggest that the distance between what the SDGs represent in principal and what their indicators measure in practice is relatively small. Whilst income remains a dominant determinant of

SDG performance, nearly half of measured progress towards achieving the SDGs cannot be explained by variation in per capita income. Of the four potential outcomes described in the introduction, the results suggest that the SDGs and indicators included in the SDG Index are closer to ‘mission accomplished’ than any other outcome. This research supports the idea that the SDGs and related indicators are largely measuring what they intended to measure. However, about half of all indicators are not included in the Index and are therefore excluded from this analysis. The next round of revisions should focus on adding new indicators, particularly those related to social outcomes.

5. CONCLUSION

This thesis contributes to sustainability measurement and policy. I develop new accounting procedures that reveal rather than conceal distinctions and connections between national and global sustainability. The unifying threads throughout the papers are an acknowledgement of the wealth theory of sustainability (Weitzman 1976; Hartwick 1977; Dasgupta and Heal 1979; Solow 1986; Arrow et al. 2012; Fenichel et al. 2018) and an interest in extending its measurement (Pearce and Atkinson 1993a; World Bank 2011; Atkinson et al. 2012; UNU-IHDP and UNEP 2012, 2014; Lange et al. 2018; Managi and Kumar 2018). The theory provides a clear wealth management rule: endowing future generations with the potential to be 'at least as well off as the present' requires that comprehensive wealth is non-declining over time. Wealth accounts are tools for assessing whether the management rule is being observed. I investigate their suitability for a globalised world and comment on how they might be augmented and extended.

The first two papers focus on the measurement of natural capital and how this relates to overall sustainability measurement. They are motivated by the knowledge that globalisation has opened markets, facilitated the spread of people, ideas, and culture, and lifted millions out of poverty. But it as also ushered in an era of unprecedented natural resource depletion and environmental change. Many of the development challenges we currently face deal with the intersection of these two trends: the benefits of economic activity and the costs of environmental degradation. International trade plays an important role in both. Responding to calls as early as James Meade (1955) and as contemporary as Joe Stiglitz (2009b), they explore the relationship between national and global sustainability.

Two complementary natural capital accounts were developed. One from the traditional territorial or production-based perspective and another from the consumption-based perspective. The former records resource depletions that take place within a country's borders, regardless of where those resources are ultimately consumed. The latter records resource depletions embodied within a country's final demand, regardless of where in the world those depletions actually took place. International trade is the link between the two, and can drive a wedge between the wealth of producing versus consuming countries. The results showed that the two perspectives generate very different maps of global natural capital depletions, and that the production versus consumption accounting gap is important for countries at all stages of development.

The second paper directly addresses carbon accounting within the wealth framework. Carbon emissions are depletions of atmospheric natural capital. But the question of where along a global supply chain for CO_2 emissions should we account for the loss of wealth remains (Davis et al. 2011). Following Arrow et al (2012), we develop greenhouse gas accounts that attribute emissions-related wealth depletions according to the location of damages (losses due to climate change). We contrast this account against traditional production based GHG accounts, and consumption-based accounts that have received attention in recent literature. Results showed that once again, the different accounting perspectives yield completely different maps of global emissions.

Several lessons can be drawn from these papers. They acknowledge that nothing in either economic or natural science requires us to restrict our measurement of sustainability to any individual accounting perspective. The reality is that the great global challenges we face are complex and multifaceted. If one believes policies to address them should be guided by evidence, then accounts such as these are a necessity. The argument is not that any individual accounting perspective is 'right', but rather that each offers insight into an important dimension of sustainability. Even for carbon accounts, where the wealth theory does give a clear economic justification for adopting the damage perspective, it is still argued that production and consumption accounts offer relevant information on the nature of emissions in the global economy. Combined, the suite of accounts from multiple perspectives tells a more complete story.

Given the large and growing role of international trade in gross world product, no measure of sustainability is complete without taking explicit account of trade. Better, more readily available evidence on global trends in resource use are relevant not just to environmental policy, but to issues of economic, fiscal, and resource security as well. Even if countries wish to take a closed perspective and only develop domestic resource strategies, they may still want accounts that illustrate global trends and strategies pursued by other countries. China's Belt and Road Initiative is an important case. Domestic facing policy makers may still want an awareness of China's global natural capital strategy. For this reason, the research adds to calls for the development of public sector balance sheets, and for these to include natural capital explicitly. This would help countries monitor the domestic resources they own and how they are managed, the global resources on which the rely and what their exposure is to shocks, and the likely fiscal implications of, say asset stranding (e.g. if fossil fuel reserves can no longer provide tax revenue).

Finally, the international dimensions described in these papers may help with efforts to build partnerships in delivering sustainability and encourage countries to think beyond borders. This would relate to SDG 17, but also to issues of resource security, least cost abatement, and industrial strategy. Early studies in this area focused on carbon policies and accounts, and revealed that issues of leakage and 'rich' versus 'developing' country 'responsibility' could be major impediments to developing global policy. A combination of production, consumption, and damage-based accounts would shed light on opportunities to for countries to work together to reduce natural capital depletions along the supply chain. Boulding (1966) wrote of the cowboy and spaceship economies and how each might approach resource scarcity. The accounting mechanisms demonstrated here put numbers to his ideas.

Shifting focus somewhat from natural capital to sustainability measurement more broadly, the final paper interrogates the sustainable development goals. As the 'North Star' for the international development community (Wackernagel et al. 2017) the SDGs and related indicators effectively 'reveal' the applied definition of sustainability adopted by the UN Member States. The goals were heralded as a paradigm shift in development thinking, moving beyond income oriented objectives to incorporate environmental and social outcomes with equal weight. Empirical analysis of actual SDG data enables us to investigate the distance between what the SDGs aspire to measure and what they actually measure. Results showed that the goals largely meet their ambition. They represent an integrated, multifaceted suite of objectives that cannot be reduced to a single measure such as per capita GDP. Of course, income components still weigh heavily, and rightly so. But about half of SDG performance is due to non-income measures, suggesting the goals do in fact represent a more rounded view of the sustainability of development.

The work is timely. 2020 is an important year for communities in economic measurement, international development, and the environment. The UN System of Environmental Economic Accounts will complete a revision of the SEEA- Experimental Ecosystem Accounts framework, which will go before the UN General Assembly for acceptance as a UN Statistical Standard. Natural capital accounts are a key element of this process, and the accounting perspectives developed here could help the design of the Standard and its adoption and implementation by countries. Data is a major challenge to conducting environmentally extended multi-regional input-output analysis. If the SEEA standards are adopted and the resulting accounts are adequately updated, metrics such as the ones presented here could be available annually within the standard suite of official economic statistics.

Similarly, the Inter-Agency Expert Group on the Sustainable Development Goals will conduct its first comprehensive review of the SDG indicators. The papers could contribute to this process, particularly in relation to indicators for SDG 12 (sustainable consumption and production) and SDG 13 (climate action). Latent variable methods including principal components analysis could become a useful tool for informing this process and communicating it to public and policy audiences (Bain et al. 2019).

This thesis aims to contribute to the field of sustainable development and economic measurement by highlighting the role of international trade in the modern economy, and what this means for management of natural capital and comprehensive wealth. The papers demonstrate the importance of developing accounts from multiple complementary perspectives to understand contributions towards national and global sustainability. But several opportunities for extensions and further research present themselves. Improved data would facilitate the regular construction of production and consumption accounts so that we could examine trends over time rather than rely on ‘snapshot’ analyses. In particular, the development of SEEA accounts would enable natural capital and ecosystem service flows to be ‘built-in’ to the social accounting matrices and official input output tables. This would enable standard economic analysis to automatically incorporate some consideration for natural capital. Improved data would also expand the coverage of natural capital within the models. Significant omissions include air quality, water (availability and quality), and biodiversity. For policy, an important next step is to build natural capital accounts into the public sector balance sheets of nations in order to better estimate public sector net worth.

Similarly, the principal components analysis of the SDGs raises interesting questions for further research. It would be interesting to investigate the trade-offs arising in the second and subsequent components. PC 2 highlighted a contrast natural versus social capital, after income variation is described by PC 1. Another component contrasted ecosystem management against inequality and poverty. This suggests that finding synergies here could be a priority for overall SDG progress. Future work could investigate the extent to which these are complementary or substitutable capitals, and whether the degree of substitutability and complementarity depends on income level.

In sum, the research presented here improves our understanding of what an evidence base for 21st century sustainability might entail. It argues that international trade and transboundary externalities are important factors in sustainability measurement and concludes that any framework that fails to account for the international dimension of sustainability is subject to unnecessary blind spots. The reality is that multidimensional challenges like climate change and sustainability are underserved by unidimensional statistics. Natural capital accounts and SDG indicators are vital to developing the evidence we need to guide policy and measure progress towards sustainability. I hope the collected essays presented here demonstrate that 21st century progress cannot be measured with 20th century statistics and that when it comes to accounting, perspective matters.

6. APPENDICES

Appendix 1 MRIO Model Description

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

Equation system (1) describes trade interactions[9] 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:

$$a_{ij}^{rr} \equiv z_{ij}^{rr} / x_j^r$$

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

(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

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[9] 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-

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

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

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

Appendix 2 List of countries and regions in the GTAP_v9 database

Country Name	GTAP Region Code		
Albania	ALB	Guatemala	GTM
Argentina	ARG	Guinea	GIN
Armenia	ARM	Honduras	HND
Australia	AUS	Hungary	HUN
Austria	AUT	India	IND
Azerbaijan	AZE	Indonesia	IDN
Bahrain	BHR	Iran	IRN
Bangladesh	BGD	Ireland	IRL
Belarus	BLR	Israel	ISR
Belgium	BEL	Italy	ITA
Benin	BEN	Jamaica	JAM
Bolivia	BOL	Japan	JPN
Botswana	BWA	Jordan	JOR
Brazil	BRA	Kazakhstan	KAZ
Brunei Darussalam	BRN	Kenya	KEN
Bulgaria	BGR	Korea, Republic Of	KOR
Burkina Faso	BFA	Kuwait	KWT
Cambodia	KHM	Kyrgyzstan	KGZ
Cameroon	CMR	Lao People's Democratic Republic	LAO
Canada	CAN	Latvia	LVA
Caribbean	XCB	Lithuania	LTU
Chile	CHL	Luxembourg	LUX
China	CHN	Madagascar	MDG
China, Hong Kong SAR	HKG	Malawi	MWI
Colombia	COL	Malaysia	MYS
Costa Rica	CRI	Malta	MLT
Cote d'Ivoire	CIV	Mauritius	MUS
Croatia	HRV	Mexico	MEX
Cyprus	CYP	Mongolia	MNG
Czech Republic	CZE	Morocco	MAR
Denmark	DNK	Mozambique	MOZ
Dominican Republic	DOM	Namibia	NAM
Ecuador	ECU	Nepal	NPL
Egypt	EGY	Netherlands	NLD
El Salvador	SLV	New Zealand	NZL
Estonia	EST	Nicaragua	NIC
Ethiopia	ETH	Nigeria	NGA
Finland	FIN	Norway	NOR
France	FRA	Oman	OMN
Georgia	GEO	Pakistan	PAK
Germany	DEU	Panama	PAN

Paraguay	PRY	Rest of South Asia	XSA
Peru	PER	Rest of Southeast Asia	XSE
Philippines	PHL	Rest of Western Africa	XWF
Poland	POL	Rest of Western Asia	XWS
Portugal	PRT	Rest of the World	XTW
Puerto Rico	PRI	Romania	ROU
Qatar	QAT	Russian Federation	RUS
Rest of Central Africa	XCF	Rwanda	RWA
Rest of Central America	XCA	Saudi Arabia	SAU
Rest of EFTA	XEF	Senegal	SEN
Rest of East Asia	XEA	Singapore	SGP
Rest of Eastern Africa	XEC	Slovakia	SVK
Rest of Eastern Europe	XEE	Slovenia	SVN
Rest of Europe	XER	South Africa	ZAF
Rest of Former Soviet Union	XSU	South Central Africa	XAC
Rest of North Africa	XNF	Spain	ESP
Rest of North America	XNA	Sri Lanka	LKA
Rest of Oceana	XOC	Sweden	SWE
Rest of South Africa Customs Union	XSC	Switzerland	CHE
Rest of South America	XSM	Taiwan	TWN
Rest of South Asia	XSA	Tanzania	TZA
Rest of Southeast Asia	XSE	Thailand	THA
Rest of Western Africa	XWF	Togo	TGO
Rest of Western Asia	XWS	Trinidad and Tobago	TTO
Paraguay	PRY	Tunisia	TUN
Peru	PER	Turkey	TUR
Philippines	PHL	Uganda	UGA
Poland	POL	Ukraine	UKR
Portugal	PRT	United Arab Emirates	ARE
Puerto Rico	PRI	United Kingdom	GBR
Qatar	QAT	United States	USA
Rest of Central Africa	XCF	Uruguay	URY
Rest of Central America	XCA	Venezuela	VEN
Rest of EFTA	XEF	Viet Nam	VNM
Rest of East Asia	XEA	Zambia	ZMB
Rest of Eastern Africa	XEC	Zimbabwe	ZWE
Rest of Eastern Europe	XEE		
Rest of Europe	XER		
Rest of Former Soviet Union	XSU		
Rest of North Africa	XNF		
Rest of North America	XNA		
Rest of Oceana	XOC		
Rest of South Africa Customs Union	XSC		
Rest of South America	XSM		

Appendix 3 Production and Consumption Resource Depletions, full results.

NATURAL RESOURCE DEPLETIONS (PRODUCTION & CONSUMPTION)

	Resource Depletions (millions of USD)						Per capita depletions & comparison to global average (GA)			
		Production		Consumption		Ratio	Production		Consumption	
	GDP	Value	% GDP	Value	% GDP	PBP/CBP	Per capita	P/GA	Per capita	C/GA
ALBANIA	12,891	197	1.53	253	1.97	0.78	67.90	0.47	87.19	0.60
ARGENTINA	530,163	4,831	0.91	5,226	0.99	0.92	115.96	0.80	125.46	0.87
ARMENIA	10,142	52	0.51	246	2.42	0.21	18.07	0.13	85.42	0.59
AUSTRALIA	1,390,557	27,292	1.96	15,088	1.09	1.81	1,221.69	8.47	675.39	4.68
AUSTRIA	431,120	534	0.12	3,773	0.88	0.14	63.65	0.44	449.56	3.12
AZERBAIJAN	65,952	8,724	13.23	784	1.19	11.13	951.07	6.59	85.42	0.59
BAHRAIN	28,777	2,297	7.98	917	3.19	2.50	1,796.86	12.46	717.70	4.98
BANGLADESH	128,638	2,164	1.68	3,419	2.66	0.63	14.06	0.10	22.21	0.15
BELARUS	61,758	522	0.85	1,739	2.82	0.30	55.12	0.38	183.57	1.27
BELGIUM	527,008	988	0.19	7,017	1.33	0.14	89.41	0.62	635.15	4.40
BENIN	7,814	33	0.42	327	4.18	0.10	3.45	0.02	34.55	0.24
BOLIVIA	23,963	763	3.18	512	2.14	1.49	75.67	0.52	50.82	0.35
BOTSWANA	15,683	314	2.00	169	1.08	1.86	153.18	1.06	82.36	0.57
BRAZIL	2,616,202	19,250	0.74	21,847	0.84	0.88	96.89	0.67	109.96	0.76
BRUNEI DARUSSALAM	18,525	2,523	13.62	346	1.87	7.29	6,404.59	44.41	878.18	6.09
BULGARIA	57,418	400	0.70	1,095	1.91	0.37	54.43	0.38	149.03	1.03
BURKINA FASO	10,724	373	3.47	126	1.18	2.95	23.17	0.16	7.85	0.05
CAMBODIA	12,830	364	2.84	615	4.80	0.59	25.02	0.17	42.33	0.29
CAMEROON	29,337	708	2.41	486	1.66	1.46	34.50	0.24	23.70	0.16
CANADA	1,788,648	32,228	1.80	18,706	1.05	1.72	938.42	6.51	544.69	3.78
CARIBBEAN	101,170	907	0.90	2,301	2.27	0.39	39.26	0.27	99.56	0.69
CHILE	252,252	3,033	1.20	4,309	1.71	0.70	176.79	1.23	251.21	1.74
CHINA	7,572,554	112,456	1.49	159,277	2.10	0.71	83.66	0.58	118.50	0.82

CHINA, HONG KONG SAR	248,514	1,675	0.67	4,474	1.80	0.37	236.92	1.64	632.72	4.39
COLOMBIA	335,415	10,095	3.01	3,518	1.05	2.87	217.54	1.51	75.80	0.53
COSTA RICA	42,263	75	0.18	547	1.29	0.14	16.34	0.11	118.92	0.82
COTE D'IVOIRE	25,382	328	1.29	409	1.61	0.80	15.72	0.11	19.55	0.14
CROATIA	62,237	209	0.34	872	1.40	0.24	48.80	0.34	203.73	1.41
CYPRUS	27,427	31	0.11	511	1.86	0.06	27.94	0.19	453.93	3.15
CZECH REPUBLIC	227,948	998	0.44	2,501	1.10	0.40	95.10	0.66	238.32	1.65
DENMARK	344,003	2,991	0.87	2,604	0.76	1.15	536.90	3.72	467.43	3.24
DOMINICAN REPUBLIC	57,747	276	0.48	1,085	1.88	0.25	27.48	0.19	108.18	0.75
ECUADOR	79,277	4,411	5.56	2,293	2.89	1.92	290.64	2.02	151.06	1.05
EGYPT	236,002	9,650	4.09	7,702	3.26	1.25	112.34	0.78	89.67	0.62
EL SALVADOR	23,139	51	0.22	441	1.91	0.12	8.29	0.06	71.28	0.49
ESTONIA	23,170	608	2.62	654	2.82	0.93	457.73	3.17	492.36	3.41
ETHIOPIA	31,953	293	0.92	752	2.35	0.39	3.26	0.02	8.35	0.06
FINLAND	273,674	618	0.23	3,115	1.14	0.20	114.68	0.80	578.10	4.01
FRANCE	2,862,680	2,846	0.10	25,446	0.89	0.11	43.55	0.30	389.42	2.70
GEORGIA	14,435	58	0.40	409	2.84	0.14	14.84	0.10	105.67	0.73
GERMANY	3,757,698	6,656	0.18	35,908	0.96	0.19	82.92	0.57	447.31	3.10
GHANA	39,566	300	0.76	806	2.04	0.37	11.94	0.08	32.08	0.22
GREECE	287,798	786	0.27	7,191	2.50	0.11	70.75	0.49	647.57	4.49
GUATEMALA	47,655	211	0.44	719	1.51	0.29	14.11	0.10	48.12	0.33
GUINEA	6,785	96	1.42	140	2.06	0.69	8.73	0.06	12.67	0.09
HONDURAS	17,710	69	0.39	401	2.26	0.17	8.31	0.06	47.98	0.33
HUNGARY	140,782	210	0.15	1,529	1.09	0.14	21.07	0.15	153.34	1.06
INDIA	1,823,050	16,742	0.92	50,037	2.74	0.33	13.42	0.09	40.12	0.28
INDONESIA	892,969	29,584	3.31	21,790	2.44	1.36	120.40	0.83	88.68	0.61
IRAN	583,500	45,689	7.83	14,017	2.40	3.26	605.22	4.20	185.67	1.29
IRELAND	239,019	401	0.17	1,840	0.77	0.22	87.51	0.61	401.92	2.79
ISRAEL	261,629	342	0.13	2,828	1.08	0.12	44.07	0.31	364.15	2.53
ITALY	2,276,292	2,899	0.13	22,368	0.98	0.13	48.83	0.34	376.69	2.61

JAMAICA	14,440	22	0.15	339	2.35	0.06	7.78	0.05	119.73	0.83
JAPAN	6,157,460	5,091	0.08	61,921	1.01	0.08	39.83	0.28	484.39	3.36
JORDAN	28,840	134	0.46	1,434	4.97	0.09	17.65	0.12	189.29	1.31
KAZAKHSTAN	192,627	16,160	8.39	3,272	1.70	4.94	976.03	6.77	197.61	1.37
KENYA	41,953	182	0.43	941	2.24	0.19	4.29	0.03	22.16	0.15
KOREA, REPUBLIC OF	1,202,464	1,662	0.14	22,171	1.84	0.07	33.29	0.23	443.99	3.08
KUWAIT	154,028	27,686	17.97	2,836	1.84	9.76	8,676.07	60.16	888.68	6.16
KYRGYZSTAN	6,198	23	0.38	322	5.19	0.07	4.23	0.03	58.38	0.40
LAO PEOPLE'S DEMOCRATIC REPUBLIC	8,749	248	2.84	307	3.51	0.81	39.20	0.27	48.46	0.34
LATVIA	28,224	121	0.43	503	1.78	0.24	58.97	0.41	244.31	1.69
LITHUANIA	43,477	56	0.13	741	1.71	0.08	18.65	0.13	244.85	1.70
LUXEMBOURG	60,005	18	0.03	616	1.03	0.03	35.59	0.25	1,187.57	8.23
MADAGASCAR	9,893	461	4.66	318	3.21	1.45	21.18	0.15	14.60	0.10
MALAWI	8,003	157	1.96	106	1.32	1.48	10.02	0.07	6.76	0.05
MALAYSIA	297,952	9,713	3.26	6,866	2.30	1.41	339.20	2.35	239.78	1.66
MALTA	9,505	2	0.02	236	2.48	0.01	5.37	0.04	566.60	3.93
MAURITIUS	11,518	42	0.36	257	2.23	0.16	33.47	0.23	205.11	1.42
MEXICO	1,171,188	8,441	0.72	12,707	1.08	0.66	70.88	0.49	106.70	0.74
MONGOLIA	10,410	849	8.16	324	3.12	2.62	307.48	2.13	117.45	0.81
MOROCCO	101,370	574	0.57	2,871	2.83	0.20	17.48	0.12	87.37	0.61
MOZAMBIQUE	13,131	352	2.68	314	2.39	1.12	14.10	0.10	12.60	0.09
NAMIBIA	12,410	326	2.63	278	2.24	1.17	147.10	1.02	125.62	0.87
NEPAL	18,914	49	0.26	326	1.72	0.15	1.81	0.01	11.92	0.08
NETHERLANDS	893,757	3,991	0.45	6,234	0.70	0.64	239.07	1.66	373.44	2.59
NEW ZEALAND	168,462	1,054	0.63	1,828	1.09	0.58	240.42	1.67	417.08	2.89
NICARAGUA	9,774	80	0.81	261	2.67	0.30	13.72	0.10	45.00	0.31
NIGERIA	411,744	29,163	7.08	5,176	1.26	5.63	179.05	1.24	31.78	0.22
NORWAY	498,832	29,053	5.82	4,055	0.81	7.17	5,865.70	40.67	818.64	5.68
OMAN	67,937	12,194	17.95	1,963	2.89	6.21	3,766.83	26.12	606.47	4.21
PAKISTAN	213,587	1,339	0.63	4,958	2.32	0.27	7.68	0.05	28.46	0.20

PANAMA	34,374	140	0.41	950	2.76	0.15	37.66	0.26	256.14	1.78
PARAGUAY	25,100	43	0.17	367	1.46	0.12	6.77	0.05	58.32	0.40
PERU	171,762	3,455	2.01	3,137	1.83	1.10	116.10	0.81	105.42	0.73
PHILIPPINES	224,143	2,593	1.16	5,643	2.52	0.46	27.22	0.19	59.23	0.41
POLAND	528,725	2,700	0.51	7,335	1.39	0.37	70.93	0.49	192.71	1.34
PORTUGAL	244,895	582	0.24	3,153	1.29	0.18	55.17	0.38	298.61	2.07
PUERTO RICO	100,352	100	0.10	793	0.79	0.13	27.16	0.19	215.65	1.50
QATAR	167,775	18,318	10.92	1,039	0.62	17.62	9,383.78	65.07	532.49	3.69
REST OF CENTRAL AFRICA	68,544	6,258	9.13	833	1.21	7.52	259.15	1.80	34.48	0.24
REST OF CENTRAL AMERICA	1,487	13	0.87	20	1.32	0.66	39.29	0.27	59.43	0.41
REST OF EAST ASIA	36,710	764	0.54	776	1.54	0.98	30.22	0.21	30.70	0.21
REST OF EASTERN AFRICA	75,182	3,641	2.08	1,238	2.11	2.94	58.03	0.40	19.73	0.14
REST OF EASTERN EUROPE	7,015	10	4.84	217	1.65	0.05	2.74	0.02	60.86	0.42
REST OF EFTA	20,415	110	0.14	314	3.09	0.35	310.15	2.15	884.76	6.14
REST OF EUROPE	100,327	1,144	1.14	2,247	2.24	0.51	82.14	0.57	161.28	1.12
REST OF FORMER SOVIET UNION	81,671	5,717	7.00	2,963	3.63	1.93	135.07	0.94	70.01	0.49
REST OF NORTH AFRICA	234,718	22,729	9.68	5,713	2.43	3.98	528.41	3.66	132.82	0.92
REST OF NORTH AMERICA	8,066	46	0.57	130	1.61	0.35	375.88	2.61	1,067.59	7.40
REST OF OCEANA	31,809	584	1.83	806	2.53	0.72	56.63	0.39	78.20	0.54
REST OF SOUTH AFRICA CUSTOMS UNION	7,609	271	3.56	123	1.62	2.20	82.33	0.57	37.48	0.26
REST OF SOUTH AMERICA	6,998	45	0.64	139	1.98	0.33	35.24	0.24	108.21	0.75
REST OF SOUTH ASIA	22,525	204	0.91	441	1.96	0.46	6.63	0.05	14.30	0.10
REST OF SOUTHEAST ASIA	61,031	1,791	2.93	1,702	2.79	1.05	34.66	0.24	32.94	0.23
REST OF THE WORLD	0	3	3.51	3	2.86	1.12				
REST OF WESTERN AFRICA	26,508	932	13.39	759	4.38	1.23	18.32	0.13	14.92	0.10
REST OF WESTERN ASIA	269,017	36,013		11,796		3.05	421.90	2.93	138.19	0.96
ROMANIA	185,363	1,098	0.59	2,365	1.28	0.46	54.48	0.38	117.38	0.81
RUSSIAN FEDERATION	2,051,662	101,086	4.93	39,746	1.94	2.54	707.09	4.90	278.02	1.93
RWANDA	6,492	167	2.58	86	1.32	1.95	15.90	0.11	8.17	0.06

SAUDI ARABIA	671,239	101,097	15.06	16,139	2.40	6.26	3,580.16	24.83	571.55	3.96
SENEGAL	14,391	116	0.81	414	2.88	0.28	8.75	0.06	31.15	0.22
SINGAPORE	275,599	47	0.02	3,009	1.09	0.02	8.99	0.06	580.46	4.02
SLOVAKIA	98,181	160	0.16	1,316	1.34	0.12	29.71	0.21	243.85	1.69
SLOVENIA	51,291	110	0.21	675	1.32	0.16	53.57	0.37	328.89	2.28
SOUTH AFRICA	416,878	4,334	1.04	6,439	1.54	0.67	83.77	0.58	124.48	0.86
SOUTH CENTRAL AFRICA	127,965	15,135	11.83	2,143	1.67	7.06	166.45	1.15	23.56	0.16
SPAIN	1,488,067	2,002	0.13	16,702	1.12	0.12	42.83	0.30	357.33	2.48
SRI LANKA	65,293	542	0.83	1,770	2.71	0.31	26.72	0.19	87.30	0.61
SWEDEN	563,110	1,051	0.19	4,356	0.77	0.24	111.24	0.77	461.00	3.20
SWITZERLAND	699,580	330	0.05	4,128	0.59	0.08	41.69	0.29	521.72	3.62
TAIWAN		886		8,350		0.11				
TANZANIA	33,879	120	0.35	451	1.33	0.27	2.52	0.02	9.49	0.07
THAILAND	370,819	4,515	1.22	9,149	2.47	0.49	66.86	0.46	135.48	0.94
TOGO	3,756	34	0.89	161	4.27	0.21	5.02	0.03	24.03	0.17
TRINIDAD AND TOBAGO	25,433	1,983	7.80	318	1.25	6.24	1,485.86	10.30	238.30	1.65
TUNISIA	45,811	971	2.12	977	2.13	0.99	90.21	0.63	90.79	0.63
TURKEY	832,546	2,525	0.30	13,084	1.57	0.19	34.40	0.24	178.23	1.24
UGANDA	20,177	496	2.46	280	1.39	1.77	14.13	0.10	7.97	0.06
UKRAINE	163,160	2,843	1.74	4,359	2.67	0.65	62.21	0.43	95.36	0.66
UNITED ARAB EMIRATES	350,908	26,149	7.45	6,716	1.91	3.89	3,015.18	20.91	774.39	5.37
UNITED KINGDOM	2,619,700	13,364	0.51	26,279	1.00	0.51	211.26	1.46	415.42	2.88
UNITED STATES	15,517,926	80,863	0.52	163,430	1.05	0.49	259.46	1.80	524.38	3.64
URUGUAY	47,962	59	0.12	501	1.05	0.12	17.30	0.12	148.10	1.03
VENEZUELA	316,482	21,126	6.68	4,139	1.31	5.10	717.02	4.97	140.47	0.97
VIET NAM	135,539	5,094	3.76	5,597	4.13	0.91	57.97	0.40	63.71	0.44
ZAMBIA	23,460	199	0.85	304	1.30	0.65	13.95	0.10	21.30	0.15
ZIMBABWE	12,098	90	0.74	206	1.71	0.44	6.26	0.04	14.34	0.10
WORLD	73,270,714	1,006,192	1.37	1,006,192	1.37	1.00	144.67	1.00	144.67	1.00

Appendix 4 Production and consumption greenhouse gas accounts

PRODUCTION AND CONSUMPTION GREENHOUSE GAS EMISSIONS

	GHG emissions (millions of 2011 USD)						GHGs per capita & comparison to global average			
		Production		Consumption		Ratio	Production		Consumption	
NAME	**GDP**	**Value**	**% GDP**	**Value**	**% GDP**	**PBP/CBP**	**Per Capita**	**P/GA**	**Per Capita**	**C/GA**
ALBANIA	12,891	669	5.19	928	7.20	0.72	230.27	0.37	319.36	0.52
ARGENTINA	530,163	26,861	5.07	26,879	5.07	1.00	644.81	1.04	645.25	1.04
ARMENIA	10,142	694	6.84	829	8.18	0.84	241.22	0.39	288.45	0.47
AUSTRALIA	1,390,557	56,951	4.10	59,534	4.28	0.96	2,549.28	4.11	2,664.90	4.30
AUSTRIA	431,120	9,177	2.13	12,882	2.99	0.71	1,093.58	1.77	1,535.10	2.48
AZERBAIJAN	65,952	4,226	6.41	4,699	7.12	0.90	460.75	0.74	512.24	0.83
BAHRAIN	28,777	3,830	13.31	2,749	9.55	1.39	2,996.63	4.84	2,150.68	3.47
BANGLADESH	128,638	7,809	6.07	10,178	7.91	0.77	50.74	0.08	66.13	0.11
BELARUS	61,758	8,261	13.38	7,739	12.53	1.07	872.06	1.41	816.89	1.32
BELGIUM	527,008	15,488	2.94	20,168	3.83	0.77	1,401.95	2.26	1,825.51	2.95
BENIN	7,814	696	8.90	1,455	18.62	0.48	73.52	0.12	153.75	0.25
BOLIVIA	23,963	2,257	9.42	2,326	9.71	0.97	223.90	0.36	230.83	0.37
BOTSWANA	15,683	669	4.27	893	5.69	0.75	326.13	0.53	435.26	0.70
BRAZIL	2,616,202	55,799	2.13	68,656	2.62	0.81	280.84	0.45	345.55	0.56
BRUNEI DARUSSALAM	18,525	1,267	6.84	1,255	6.77	1.01	3,216.89	5.19	3,184.31	5.14
BULGARIA	57,418	7,158	12.47	5,513	9.60	1.30	974.13	1.57	750.18	1.21
BURKINA FASO	10,724	284	2.65	365	3.40	0.78	17.66	0.03	22.70	0.04
CAMBODIA	12,830	715	5.57	1,273	9.92	0.56	49.16	0.08	87.54	0.14
CAMEROON	29,337	862	2.94	1,116	3.81	0.77	42.03	0.07	54.40	0.09
CANADA	1,788,648	78,467	4.39	76,750	4.29	1.02	2,284.81	3.69	2,234.83	3.61
CARIBBEAN	101,170	6,151	6.08	7,300	7.22	0.84	266.15	0.43	315.84	0.51
CHILE	252,252	11,962	4.74	13,413	5.32	0.89	697.38	1.13	781.94	1.26
CHINA	7,572,554	1,086,166	14.34	899,264	11.88	1.21	808.08	1.30	669.03	1.08
CHINA, HONG KONG SAR	248,514	12,542	5.05	15,142	6.09	0.83	1,773.64	2.86	2,141.27	3.46

COLOMBIA	335,415	10,225	3.05	12,561	3.74	0.81	220.35	0.36	270.67	0.44
COSTA RICA	42,263	1,064	2.52	1,669	3.95	0.64	231.23	0.37	362.68	0.59
COTE D'IVOIRE	25,382	947	3.73	1,183	4.66	0.80	45.34	0.07	56.64	0.09
CROATIA	62,237	2,906	4.67	3,521	5.66	0.83	678.92	1.10	822.47	1.33
CYPRUS	27,427	2,005	7.31	1,744	6.36	1.15	1,782.77	2.88	1,550.17	2.50
CZECH REPUBLIC	227,948	15,069	6.61	13,130	5.76	1.15	1,435.69	2.32	1,250.98	2.02
DENMARK	344,003	9,566	2.78	9,346	2.72	1.02	1,717.26	2.77	1,677.83	2.71
DOMINICAN REPUBLIC	57,747	2,920	5.06	3,319	5.75	0.88	291.21	0.47	331.04	0.53
ECUADOR	79,277	4,610	5.82	5,942	7.50	0.78	303.74	0.49	391.50	0.63
EGYPT	236,002	26,839	11.37	26,262	11.13	1.02	312.45	0.50	305.74	0.49
EL SALVADOR	23,139	983	4.25	1,374	5.94	0.72	158.68	0.26	221.82	0.36
ESTONIA	23,170	2,484	10.72	2,080	8.98	1.19	1,870.98	3.02	1,567.01	2.53
ETHIOPIA	31,953	1,131	3.54	1,804	5.64	0.63	12.56	0.02	20.03	0.03
FINLAND	273,674	8,308	3.04	9,936	3.63	0.84	1,541.93	2.49	1,843.94	2.98
FRANCE	2,862,680	53,681	1.88	73,923	2.58	0.73	821.54	1.33	1,131.31	1.83
GEORGIA	14,435	994	6.88	1,334	9.24	0.74	256.43	0.41	344.36	0.56
GERMANY	3,757,698	104,199	2.77	126,065	3.35	0.83	1,298.02	2.10	1,570.41	2.53
GHANA	39,566	1,744	4.41	2,738	6.92	0.64	69.41	0.11	109.01	0.18
GREECE	287,798	30,440	10.58	24,461	8.50	1.24	2,741.17	4.42	2,202.76	3.56
GUATEMALA	47,655	1,580	3.32	2,357	4.95	0.67	105.70	0.17	157.64	0.25
GUINEA	6,785	139	2.05	401	5.91	0.35	12.60	0.02	36.33	0.06
HONDURAS	17,710	1,120	6.32	1,333	7.53	0.84	134.08	0.22	159.66	0.26
HUNGARY	140,782	6,614	4.70	7,500	5.33	0.88	663.26	1.07	752.13	1.21
INDIA	1,823,050	265,697	14.57	251,665	13.80	1.06	213.03	0.34	201.78	0.33
INDONESIA	892,969	58,064	6.50	63,876	7.15	0.91	236.31	0.38	259.97	0.42
IRAN	583,500	72,619	12.45	70,745	12.12	1.03	961.95	1.55	937.13	1.51
IRELAND	239,019	6,618	2.77	6,094	2.55	1.09	1,445.99	2.33	1,331.55	2.15
ISRAEL	261,629	10,404	3.98	12,098	4.62	0.86	1,339.70	2.16	1,557.85	2.51
ITALY	2,276,292	58,432	2.57	75,145	3.30	0.78	984.05	1.59	1,265.51	2.04
JAMAICA	14,440	1,210	8.38	1,262	8.74	0.96	427.48	0.69	445.99	0.72

JAPAN	6,157,460	154,512	2.51	183,623	2.98	0.84	1,208.70	1.95	1,436.43	2.32
JORDAN	28,840	3,171	11.00	4,220	14.63	0.75	418.68	0.68	557.09	0.90
KAZAKHSTAN	192,627	37,437	19.44	24,556	12.75	1.52	2,261.16	3.65	1,483.15	2.39
KENYA	41,953	1,937	4.62	2,713	6.47	0.71	45.58	0.07	63.85	0.10
KOREA, REPUBLIC OF	1,202,464	75,285	6.26	69,827	5.81	1.08	1,507.60	2.43	1,398.32	2.26
KUWAIT	154,028	12,557	8.15	10,440	6.78	1.20	3,935.15	6.35	3,271.54	5.28
KYRGYZSTAN	6,198	1,078	17.39	1,780	28.73	0.61	195.49	0.32	322.86	0.52
LAO PEOPLE'S DEMOCRATIC REPUBLIC	8,749	285	3.25	621	7.10	0.46	44.93	0.07	98.05	0.16
LATVIA	28,224	1,457	5.16	1,881	6.66	0.77	707.50	1.14	913.11	1.47
LITHUANIA	43,477	1,691	3.89	2,583	5.94	0.65	558.36	0.90	852.88	1.38
LUXEMBOURG	60,005	2,358	3.93	2,176	3.63	1.08	4,549.58	7.34	4,198.28	6.78
MADAGASCAR	9,893	316	3.19	487	4.92	0.65	14.52	0.02	22.38	0.04
MALAWI	8,003	160	2.00	338	4.22	0.47	10.23	0.02	21.61	0.03
MALAYSIA	297,952	30,409	10.21	25,204	8.46	1.21	1,061.95	1.71	880.19	1.42
MALTA	9,505	583	6.14	897	9.44	0.65	1,401.44	2.26	2,155.60	3.48
MAURITIUS	11,518	780	6.77	953	8.28	0.82	622.55	1.00	761.34	1.23
MEXICO	1,171,188	63,615	5.43	66,656	5.69	0.95	534.17	0.86	559.71	0.90
MONGOLIA	10,410	1,901	18.26	2,225	21.37	0.85	688.24	1.11	805.56	1.30
MOROCCO	101,370	7,545	7.44	8,585	8.47	0.88	229.61	0.37	261.26	0.42
MOZAMBIQUE	13,131	459	3.50	1,034	7.87	0.44	18.42	0.03	41.46	0.07
NAMIBIA	12,410	455	3.67	571	4.60	0.80	205.54	0.33	257.61	0.42
NEPAL	18,914	649	3.43	1,448	7.65	0.45	23.76	0.04	52.97	0.09
NETHERLANDS	893,757	25,539	2.86	24,935	2.79	1.02	1,529.89	2.47	1,493.71	2.41
NEW ZEALAND	168,462	4,846	2.88	5,575	3.31	0.87	1,105.48	1.78	1,271.60	2.05
NICARAGUA	9,774	645	6.60	814	8.33	0.79	111.09	0.18	140.16	0.23
NIGERIA	411,744	9,666	2.35	14,335	3.48	0.67	59.34	0.10	88.01	0.14
NORWAY	498,832	9,893	1.98	9,374	1.88	1.06	1,997.25	3.22	1,892.55	3.05
OMAN	67,937	9,055	13.33	7,267	10.70	1.25	2,797.04	4.51	2,244.77	3.62
PAKISTAN	213,587	19,551	9.15	21,566	10.10	0.91	112.24	0.18	123.81	0.20
PANAMA	34,374	3,258	9.48	3,515	10.23	0.93	878.71	1.42	948.01	1.53

PARAGUAY	25,100	705	2.81	1,292	5.15	0.55	112.06	0.18	205.26	0.33
PERU	171,762	6,611	3.85	9,085	5.29	0.73	222.13	0.36	305.28	0.49
PHILIPPINES	224,143	11,783	5.26	14,715	6.56	0.80	123.67	0.20	154.44	0.25
POLAND	528,725	43,516	8.23	41,482	7.85	1.05	1,143.25	1.85	1,089.81	1.76
PORTUGAL	244,895	8,011	3.27	8,673	3.54	0.92	758.79	1.22	821.48	1.33
PUERTO RICO	100,352	1,662	1.66	2,514	2.50	0.66	451.92	0.73	683.31	1.10
QATAR	167,775	9,680	5.77	5,746	3.42	1.68	4,959.11	8.00	2,943.47	4.75
REST OF CENTRAL AFRICA	68,544	1,569	2.29	2,427	3.54	0.65	64.96	0.10	100.52	0.16
REST OF CENTRAL AMERICA	1,487	39	2.61	66	4.44	0.59	117.78	0.19	200.54	0.32
REST OF EAST ASIA	36,710	8,685	23.66	6,846	18.65	1.27	343.68	0.55	270.89	0.44
REST OF EASTERN AFRICA	75,182	2,439	3.24	3,932	5.23	0.62	38.87	0.06	62.66	0.10
REST OF EASTERN EUROPE	7,015	1,171	16.70	1,515	21.60	0.77	329.06	0.53	425.61	0.69
REST OF EFTA	20,415	911	4.46	919	4.50	0.99	2,563.46	4.14	2,587.74	4.18
REST OF EUROPE	100,327	14,128	14.08	12,643	12.60	1.12	1,014.14	1.64	907.57	1.46
REST OF FORMER SOVIET UNION	81,671	25,206	30.86	22,898	28.04	1.10	595.47	0.96	540.95	0.87
REST OF NORTH AFRICA	234,718	19,951	8.50	21,760	9.27	0.92	463.83	0.75	505.89	0.82
REST OF NORTH AMERICA	8,066	281	3.48	545	6.76	0.52	2,313.91	3.73	4,487.86	7.24
REST OF OCEANA	31,809	1,886	5.93	3,179	9.99	0.59	182.98	0.30	308.45	0.50
REST OF SOUTH AFRICA CUSTOMS UNION	7,609	178	2.34	302	3.98	0.59	54.10	0.09	91.96	0.15
REST OF SOUTH AMERICA	6,998	218	3.11	437	6.25	0.50	169.87	0.27	341.33	0.55
REST OF SOUTH ASIA	22,525	815	3.62	2,177	9.66	0.37	26.45	0.04	70.61	0.11
REST OF SOUTHEAST ASIA	61,031	1,238	2.03	2,277	3.73	0.54	23.95	0.04	44.06	0.07
REST OF THE WORLD	0	11		11		1.04				
REST OF WESTERN AFRICA	26,508	888	3.35	3,005	11.33	0.30	17.46	0.03	59.08	0.10
REST OF WESTERN ASIA	269,017	29,674	11.03	35,661	13.26	0.83	347.64	0.56	417.77	0.67
ROMANIA	185,363	11,728	6.33	12,136	6.55	0.97	582.11	0.94	602.33	0.97
RUSSIAN FEDERATION	2,051,662	225,524	10.99	200,729	9.78	1.12	1,577.53	2.55	1,404.08	2.27
RWANDA	6,492	173	2.67	257	3.95	0.67	16.46	0.03	24.40	0.04
SAUDI ARABIA	671,239	54,766	8.16	57,669	8.59	0.95	1,939.44	3.13	2,042.26	3.30
SENEGAL	14,391	865	6.01	1,099	7.63	0.79	65.05	0.10	82.60	0.13

SINGAPORE	275,599	9,904	3.59	10,096	3.66	0.98	1,910.61	3.08	1,947.57	3.14
SLOVAKIA	98,181	4,114	4.19	5,350	5.45	0.77	762.14	1.23	991.08	1.60
SLOVENIA	51,291	2,370	4.62	2,689	5.24	0.88	1,154.35	1.86	1,309.66	2.11
SOUTH AFRICA	416,878	52,695	12.64	38,838	9.32	1.36	1,018.66	1.64	750.79	1.21
SOUTH CENTRAL AFRICA	127,965	2,584	2.02	4,158	3.25	0.62	28.42	0.05	45.73	0.07
SPAIN	1,488,067	42,201	2.84	47,658	3.20	0.89	902.84	1.46	1,019.58	1.65
SRI LANKA	65,293	2,711	4.15	4,246	6.50	0.64	133.74	0.22	209.48	0.34
SWEDEN	563,110	7,053	1.25	11,454	2.03	0.62	746.41	1.20	1,212.11	1.96
SWITZERLAND	699,580	6,227	0.89	14,023	2.00	0.44	787.02	1.27	1,772.26	2.86
TAIWAN		36,649		26,825		1.37				
TANZANIA	33,879	1,053	3.11	1,803	5.32	0.58	22.13	0.04	37.91	0.06
THAILAND	370,819	36,329	9.80	32,449	8.75	1.12	537.97	0.87	480.50	0.78
TOGO	3,756	321	8.55	626	16.68	0.51	48.09	0.08	93.78	0.15
TRINIDAD AND TOBAGO	25,433	3,364	13.23	1,619	6.37	2.08	2,520.60	4.07	1,212.81	1.96
TUNISIA	45,811	3,386	7.39	3,431	7.49	0.99	314.64	0.51	318.80	0.51
TURKEY	832,546	42,853	5.15	50,192	6.03	0.85	583.75	0.94	683.72	1.10
UGANDA	20,177	459	2.28	796	3.94	0.58	13.09	0.02	22.67	0.04
UKRAINE	163,160	37,309	22.87	28,677	17.58	1.30	816.28	1.32	627.41	1.01
UNITED ARAB EMIRATES	350,908	22,681	6.46	32,401	9.23	0.70	2,615.29	4.22	3,736.08	6.03
UNITED KINGDOM	2,619,700	70,612	2.70	93,869	3.58	0.75	1,116.24	1.80	1,483.89	2.40
UNITED STATES	15,517,926	766,199	4.94	832,509	5.36	0.92	2,458.42	3.97	2,671.18	4.31
URUGUAY	47,962	1,050	2.19	1,650	3.44	0.64	310.28	0.50	487.43	0.79
VENEZUELA	316,482	22,829	7.21	22,803	7.21	1.00	774.82	1.25	773.94	1.25
VIET NAM	135,539	19,088	14.08	20,015	14.77	0.95	217.25	0.35	227.80	0.37
ZAMBIA	23,460	288	1.23	615	2.62	0.47	20.22	0.03	43.10	0.07
ZIMBABWE	12,098	1,430	11.82	1,587	13.12	0.90	99.41	0.16	110.31	0.18
WORLD	72,642,218	4,322,741	5.95	4,322,741	5.95	1.00	619.56	1.00	619.56	1.00

Appendix 5 List of Indicators included in SDG Index (2019)

Goal	**Description**	**Data**
SDG 1	No Poverty	Poverty headcount ratio at $1.90/day (% population)
SDG 1		Poverty headcount ratio at $3.20/day (% population)
SDG 1		Poverty rate after taxes and transfers, Poverty line 50% (% population)
SDG 2	Zero Hunger	Prevalence of undernourishment (% population)
SDG 2		Prevalence of stunting (low height-for-age) in children under 5 years of age (%)
SDG 2		Prevalence of wasting in children under 5 years of age (%)
SDG 2		Prevalence of obesity, BMI ≥ 30 (% adult population)
SDG 2		Cereal yield (t/ha)
SDG 2		Sustainable Nitrogen Management Index
SDG 2		Yield gap closure (%)
SDG 2		Human Trophic Level (best 2 - 3 worst)
SDG 3	Good Health & Wellbeing	Maternal mortality rate (per 100,000 live births)
SDG 3		Neonatal mortality rate (per 1,000 live births)
SDG 3		Mortality rate, under-5 (per 1,000 live births)
SDG 3		Incidence of tuberculosis (per 100,000 population)
SDG 3		New HIV infections (per 1,000)
SDG 3		Age-standardised death rate due to cardiovascular disease, cancer, diabetes, and chronic respiratory disease in populations age 30–70 years (per 100,000 population)
SDG 3		Age-standardised death rate attributable to household air pollution and ambient air pollution (per 100,000 population)
SDG 3		Traffic deaths rate (per 100,000 population)
SDG 3		Life Expectancy at birth (years)
SDG 3		Adolescent fertility rate (births per 1,000 women ages 15-19)
SDG 3		Births attended by skilled health personnel (%)
SDG 3		Percentage of surviving infants who received 2 WHO-recommended vaccines (%)
SDG 3		Universal Health Coverage Tracer Index (0-100)
SDG 3		Subjective Wellbeing (average ladder score, 0-10)
SDG 3		Gap in life expectancy at birth among regions (years)
SDG 3		Gap in self-reported health by income (0-100)
SDG 3		Daily smokers (% population age 15+)
SDG 4	Quality Education	Net primary enrolment rate (%)
SDG 4		Lower secondary completion rate (%)
SDG 4		Literacy rate of 15-24 year olds, both sexes (%)
SDG 4		Enrollment in early childhood learning program (% ages 4-6)
SDG 4		Population age 25-34 with tertiary education (%)
SDG 4		PISA score (0-600)
SDG 4		Percentage of variation in science performance explained by students' socio-economic status
SDG 4		Students performing below level 2 in science (%)
SDG 4		Resilient students (%)

SDG 5	Gender Equality	Demand for family planning satisfied by modern methods (% women married or in unions, ages 15-49)
SDG 5		Ratio of female to male mean years of schooling of population age 25 and above
SDG 5		Ratio of female to male labour force participation rate
SDG 5		Seats held by women in national parliaments (%)
SDG 5		Gender wage gap (Total, % male median wage)
SDG 5		Gender gap in minutes spent per day doing unpaid work (minutes)
SDG 6	Clean Water	Population using at least basic drinking water services (%)
SDG 6		Population using at least basic sanitation services (%)
SDG 6		Freshwater withdrawal as % total renewable water resources
SDG 6		Imported groundwater depletion (m3/year/capita)
SDG 6		Anthropogenic wastewater that receives treatment (%)
SDG 6		Population using safely managed water services (%)
SDG 6		Population using safely managed sanitation services (%)
SDG 7	Affordable & Clean Energy	Access to electricity (% population)
SDG 7		Access to clean fuels & technology for cooking (% population)
SDG 7		CO2 emissions from fuel combustion / electricity output (MtCO2/TWh)
SDG 7		Share of renewable energy in total final energy consumption (%)
SDG 8	Decent Work & Economic Growth	Adjusted Growth (%)
SDG 8		Prevalence of Modern Slavery (victims per 1,000 population)
SDG 8		Adults (15 years and older) with an account at a bank or other financial institution or with a mobile-money-service provider (%)
SDG 8		Unemployment rate (% total labor force)
SDG 8		Fatal work-related accidents embodied in imports (deaths per 100,000)
SDG 8		Employment-to-Population ratio (%)
SDG 8		Youth not in employment, education or training (NEET) (%)
SDG 9	Industry, Innovation & Manufacturing	Population using the internet (%)
SDG 9		Mobile broadband subscriptions (per 100 inhabitants)
SDG 9		Logistics performance index: Quality of trade and transport-related infrastructure (1=low to 5=high)
SDG 9		The Times Higher Education Universities Ranking : Average score of top 3 universities (0-100)
SDG 9		Number of scientific and technical journal articles (per 1,000 population)
SDG 9		Research and development expenditure (% GDP)
SDG 9		Research and development researchers (per 1,000 employed)
SDG 9		Triadic Patent Families filed (per million population)
SDG 9		Gap in internet access by income (%)
SDG 9		Women in science and engineering (%)
SDG 10	Reduced Inequality	Gini Coefficient adjusted for top income (1-100)
SDG 10		Palma ratio
SDG 10		Elderly Poverty Rate (%)

SDG 11	Sustainable Cities & Communities	Annual mean concentration of particulate matter of less than 2.5 microns of diameter (PM2.5) (µg/m3)
SDG 11		Improved water source, piped (% urban population with access)
SDG 11		Satisfaction with public transport (%)
SDG 11		Rent overburden rate (%)
SDG 12	Sustaonable Consumption & Production	Municipal Solid Waste (kg/day/capita)
SDG 12		E-waste generated (kg/capita)
SDG 12		Production-based SO2 emissions (kg/capita)
SDG 12		Imported SO2 emissions (kg/capita)
SDG 12		Nitrogen production footprint (kg/capita)
SDG 12		Net imported emissions of reactive nitrogen (kg/capita)
SDG 12		Non-Recycled Municipal Solid Waste (kg/day/capita)
SDG 13	Climate Action	Energy-related CO2 emissions per capita (tCO2/capita)
SDG 13		Imported CO2 emissions, technology-adjusted (tCO2/capita)
SDG 13		People affected by climate-related disasters (per 100,000 population)
SDG 13		CO2 emissions embodied in fossil fuel exports (kg/capita)
SDG 13		Effective Carbon Rate from all non-road energy, excluding emissions from biomass (€/tCO2)
SDG 14	Life Below Water	Mean area that is protected in marine sites important to biodiversity (%)
SDG 14		Ocean Health Index Goal - Clean Waters (0-100)
SDG 14		Percentage of Fish Stocks overexploited or collapsed by EEZ (%)
SDG 14		Fish caught by trawling (%)
SDG 15	Life on Land	Mean area that is protected in terrestrial sites important to biodiversity (%)
SDG 15		Mean area that is protected in freshwater sites important to biodiversity (%)
SDG 15		Red List Index of species survival (0-1)
SDG 15		Permanent Deforestation (5 year average annual %)
SDG 15		Imported biodiversity threats (threats per million population)
SDG 16	Peace, Justics & Strong Institutions	Homicides (per 100,000 population)
SDG 16		Unsentenced detainees (%)
SDG 16		Proportion of the population who feel safe walking alone at night in the city or area where they live (%)
SDG 16		Property Rights (1-7)
SDG 16		Birth registrations with civil authority, children under 5 years of age (%)
SDG 16		Corruption Perception Index (0-100)
SDG 16		Children 5–14 years old involved in child labour (%)
SDG 16		Transfers of major conventional weapons (exports) (constant 1990 US$ million per 100,000 population)
SDG 16		Freedom of Press Index (best 0 - 100 worst)
SDG 16		Prison Population (per 100,000 people)
SDG 17	Partnerships for the Goals	Government Health and Education spending (% GDP)

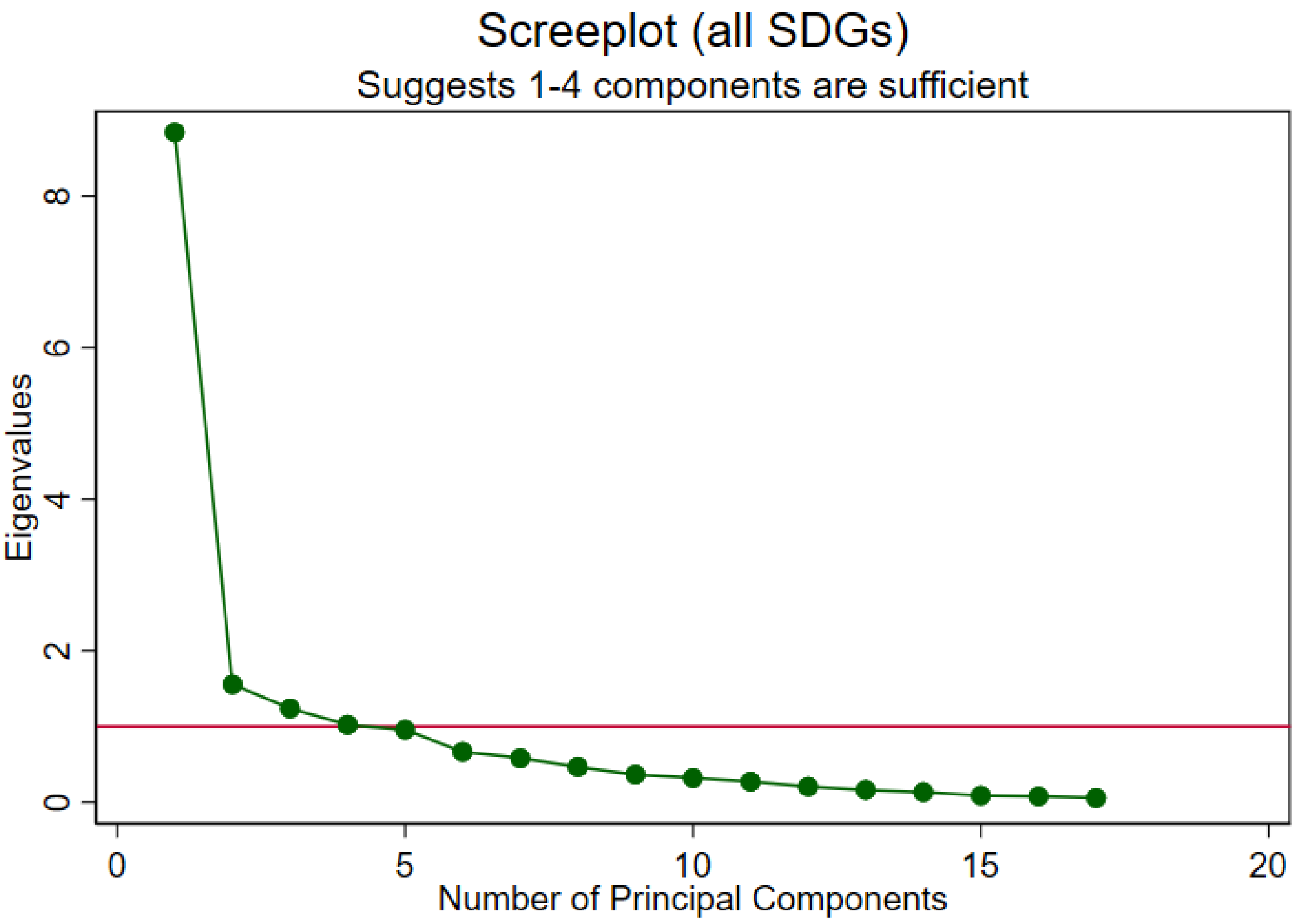
SDG 17		For high-income and all OECD DAC countries: International concessional public finance, including official development assistance (% GNI)
SDG 17		Other countries : Government Revenue excluding Grants (% GDP)
SDG 17		Tax Haven Score (best 0-5 worst)
SDG 17		Financial Secrecy Score (best 0-100 worst)

Appendix 6 Component loadings for all 17 Principal Components (Eigenvalues)

SDG	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14	PC15	PC16	PC17	UNEXPLAINED
SDG1	0.28	-0.15	0.05	0.19	0.05	0.07	-0.46	0.03	-0.09	0.06	0.10	0.10	0.52	-0.04	-0.34	0.47	-0.04	0
SDG2	0.24	0.25	-0.20	0.16	0.13	0.25	0.15	-0.50	0.25	0.44	-0.25	-0.03	0.17	-0.27	-0.08	-0.20	-0.02	0
SDG3	0.32	-0.07	0.03	0.08	0.01	0.02	-0.12	0.10	-0.07	-0.12	0.02	-0.10	-0.11	-0.02	-0.26	-0.36	0.79	0
SDG4	0.29	-0.02	0.16	0.19	-0.02	0.02	-0.13	-0.05	0.20	0.30	0.10	0.34	-0.69	0.15	0.02	0.29	-0.01	0
SDG5	0.25	0.20	0.22	-0.14	-0.04	-0.13	0.54	0.03	-0.46	0.24	0.21	0.32	0.19	0.21	-0.16	-0.03	0.00	0
SDG6	0.30	0.04	0.08	0.02	0.02	0.00	-0.08	-0.19	-0.08	0.07	0.07	-0.66	0.02	0.59	0.21	0.01	-0.11	0
SDG7	0.29	-0.08	0.21	0.18	0.19	-0.07	-0.32	-0.05	-0.24	-0.16	0.06	0.24	0.02	-0.16	0.31	-0.55	-0.35	0
SDG8	0.25	0.25	-0.04	0.15	-0.25	0.14	0.22	-0.05	0.41	-0.52	0.50	0.02	0.07	-0.05	-0.07	-0.01	-0.13	0
SDG9	0.30	0.06	-0.17	-0.09	0.00	-0.09	0.10	-0.20	-0.15	-0.30	-0.26	0.16	0.08	-0.13	0.58	0.41	0.29	0
SDG10	0.12	-0.20	-0.70	-0.13	0.07	0.37	-0.01	0.17	-0.28	0.14	0.36	0.01	-0.13	-0.03	0.09	-0.03	-0.08	0
SDG11	0.27	-0.06	0.27	0.05	-0.12	0.09	0.20	0.56	0.06	0.24	-0.04	-0.36	0.01	-0.47	0.21	0.10	-0.07	0
SDG12	-0.29	-0.01	0.15	0.23	0.11	0.25	-0.02	0.13	0.24	0.25	0.28	0.22	0.33	0.25	0.48	-0.07	0.32	0
SDG13	-0.16	0.30	-0.02	0.63	0.29	0.29	0.16	0.18	-0.32	-0.24	-0.22	-0.06	-0.14	0.08	-0.10	0.12	-0.04	0
SDG14	-0.01	0.50	0.26	-0.51	-0.03	0.55	-0.32	0.05	-0.09	-0.06	-0.06	0.04	-0.06	-0.02	0.00	0.02	0.01	0
SDG15	0.05	0.54	-0.23	-0.09	0.47	-0.50	-0.17	0.28	0.17	0.10	0.16	-0.04	0.02	-0.03	0.02	0.03	0.03	0
SDG16	0.28	-0.07	-0.20	-0.09	-0.06	0.09	0.07	0.42	0.31	-0.08	-0.51	0.25	0.14	0.42	-0.05	-0.16	-0.15	0
SDG17	0.08	-0.35	0.23	-0.27	0.74	0.18	0.27	-0.08	0.19	-0.18	0.07	-0.03	-0.03	-0.01	-0.10	0.09	-0.02	0
% OF TOTAL VARIANCE	**52.00**	**9.15**	**7.28**	**6.01**	**5.62**	**3.91**	**3.42**	**2.74**	**2.15**	**1.88**	**1.60**	**1.21**	**0.95**	**0.78**	**0.51**	**0.45**	**0.33**	**100%**

Appendix 5 Component loadings describe the weight of each variable on each principal component. The last row indicates the share of original total variance described by each component.

Appendix 7 Scree plot of PCA on 17 SDG Index Scores



Appendix 6 shows a scree plot of Eigenvalues against the number of principal components. Eigenvalues greater than 1 (above the red line) describe 74.44% of original variance. The figure shows that between 1 and 4 components are sufficient.

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