Chapter 2: Measuring for the future, not the past

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Abstract

Mainstream economic statistics are a snapshot of the portion of the economy that falls inside the production boundary as defined in the System of National Accounts (SNA). This raises accounting challenges, given the economy's reliance on largely unmeasured natural capital services. One issue is that the SNA records flow measures over the past. Augmenting them with full wealth accounts is a necessary extension for assessing the resilience of the economy. Wealth accounting, including natural capital, embeds sustainability through the valuation of asset stocks, which reflect anticipated future benefit flows; and wealth accounting, including the distribution of access to assets, better captures changes in social welfare. A corollary accounting challenge is that the present SNA framework is derived from backward-looking economic structures. At a time of substantial technological and behavioural transition, the dynamics of change imply there will be large discontinuous changes in the shadow prices needed for the valuation of natural capital services. In this paper we advocate a substantial expansion of natural capital measurement, including consideration of asset correlations and extended valuation techniques, to enhance mainstream economic indicators relating to risk, growth, and productivity. The task is fundamentally important because measurements change future behaviour and thus affect the outcomes they measure.

JEL codes: E01, Q50, D63
Key words: natural capital, valuation, welfare, risk

Introduction: the measurement challenge and missing capitals

Climate change has been described as, "The greatest market failure the world has ever seen," (Stern 2007). It results from a combination of multiple and dynamic market failures, with implications for every field of economics, including labour, health, finance, fiscal and monetary stability, and productivity. Yet the climatological and ecological fundamentals are largely absent from the statistics that economists might use to model and assess the consequences of climate change or biodiversity loss. Economic analysis is significantly inadequate if trade statistics ignore the depletion of natural capital, asset pricing models ignore ecological risks, and productivity measurement ignores risks and impacts due to air pollution and temperature extremes. Useful economic models and predictions need appropriate data.

The conventions, definitions and assumptions that underpin conventional economic measurement largely reflect SNA's origins as a framework for macroeconomic policy developed in a wartime context (Coyle 2014). They exclude many natural assets because they lie outside the asset boundary (because they are not owned) or the production boundary (because the activities in question are not carried out by an institutional unit with ownership rights) or because they cross national boundaries and ownership rights are not feasible (SNA2008, 1D). This framework was developed at a time when natural resources seemed relatively abundant, and when - for many people - the natural world seemed stable. Measurement of changes in the environment outside the SNA production and asset boundaries were not a pressing concern.

The situation has changed dramatically since the 2008 revision of the SNA. The effects of human activity on economically-vital aspects of the natural world are demonstrable and unsustainable. Even as the current revision of the SNA (2025) is under way, there have been significant changes in economic measurement. The Dasgupta Review on the Economics of Biodiversity forcefully stated the case for incorporating measures of natural capital into economic statistics (Dasgupta 2021). It is also reflected in the development of the System of Environmental Economic Accounting (SEEA) as the formal UN standard for natural capital accounting, the UN's Statistics Commission's 2021 adoption of statistical standards for ecosystem accounting, and the development of natural capital accounts by some National Statistical Offices (NSOs), including the UK and the US.

The revision of the System of National Accounts under way and due for publication in 2025 has a focus on missing capitals, natural capital prominent among them. However, the formal standard will be the start of the process of developing natural capital accounts; the US has only recently announced it will begin work on natural capital accounts. The task is immense and will require new sources of data and data collection techniques. The spatial aspects will be challenging. However, the current backward-looking snapshot of the economy inside production and asset boundaries as defined in ways that exclude fundamental aspects of nature is inadequate for informing forward-looking business and policy decisions. The collection of physical natural capital data, and the valuation of natural capital assets using (inevitably imperfect) shadow prices is essential if the aim of gathering statistics is, rather than enabling an autopsy of the economy, to diagnose its ills and help decision-makers address them.

Such initiatives are motivated by a growing recognition that a new, or at least substantially extended, economic and measurement framework is needed. Responding to global demand for going 'Beyond GDP', governments from Canada to New Zealand are compiling wellbeing statistics, and there are advocates for using direct well-being measures (such as life satisfaction) as a policy target (De Neve 2020). The UN's Inclusive Wealth Reports and World Bank's Changing Wealth of Nations series measure wealth across most major economies, with the World Bank extending this to consider social capital for the first time in 2021[1] (World Bank 2021). The Covid-19 pandemic underscored the importance of recent

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[1] World Bank (2021) notes the importance of social capital in determining economic outcomes and explores how it could be measured, but due a lack of measurement and valuation, social capital is not incorporated into the core accounts at this time. Dasgupta (2021, p325) presents social capital as an enabling asset that adds value to natural, human, and physical capital by facilitating their use.

initiatives to incorporate health in to human capital measures (Kraay 2019; Angrist et al 2021). Other suggestions include dashboards or suites of indicators (including those in several of the Sustainable Development Goals). While these approaches all have different merits, policymakers and businesses need statistics that can act as a forward-looking guide to enable diagnosis and action. This points to a limitation not only of the rear-view mirror of the national accounts, but also of many of the alternative proposals, which are also snapshots of the recent past. Comprehensive asset stock statistics directly and consistently correspond with SNA flow measures, allowing a richer assessment of the functional relationship and returns to assets in the production function.

Taking an inclusive wealth approach to economic measurement is not just about extending accounting boundaries to incorporate a broader slice of economic activity: it entails thinking critically about the whole suite of assets on which that activity relies, how their stocks are changing, and how they will contribute to wellbeing in the future. Natural capital accounting can provide a forward-looking tool of exactly this kind, combining environmental and economic knowledge (Vardon et al 2022). Advantages of such an approach include that assets embed a concern for the future because their current value is determined by expected risk-adjusted future flows of capital services, and the net change in assets determines the economy's productive capacity over time. Furthermore, it responds to the demands to go 'Beyond GDP', because an increase in net inclusive wealth (or equivalently net investment) is invariably associated with an increase in social welfare, including for future generations. This is a formal equivalence because intergenerational well-being will depend on the flow of consumption at all future dates, which will depend on the stock of assets and the capital services they provide (Dasgupta and Mäler 2000).

An important characteristic of natural capital accounting concerns the geographical scope of the statistics. Environmentally-relevant spatial scales are unlikely to coincide with the national or sub-national boundaries used for conventional economic measurement. These are relevant because policy and business decisions concern these political geographies. Important elements of natural capital – referred to as 'global public goods' (Arrow et al 2012) – cross nation state boundaries. For example, critical marine fish stocks move through national and international waters, 60% of the world's freshwater flows through transboundary lake and river basins (UN-Water 2021), and air pollution, greenhouse gas emissions and climate change are also obvious examples. In these cases, accounting systems fitted to national borders may conceal rather than reveal important changes in the natural capital on which economies rely.

The boundaries issue also highlights distributional questions. If inclusive wealth is to function as a better, forward-looking measure of social welfare, its distributional aspects are important, and distributional criteria ought in principle to be reflected in shadow prices. Climate change and biodiversity impacts are exacerbating and creating inequalities within and between countries. Natural capital – like other forms of public wealth – is more important to people with low monetary incomes and wealth. Indeed, Drupp et al (2018) show that more equal societies place higher value on environmental public goods and that the non-market benefits of environmental policy disproportionately benefit the poor. However, more deprived communities tend to be located within lower quality natural environments which exacerbate inequalities associated with tighter environmental constraints and reduced access to environmental services (Mullin et al. 2018).

A wealth-based measurement framework will only improve economic and environmental policies and outcomes if the required data are collected and used in mainstream economic analyses. This requires at least three conditions to be satisfied. First, accounts recording the stocks of natural, social, human, and physical capital must be produced at regular intervals. Second, these wealth accounts must be fully consistent with the social accounting matrices that already underpin the macroeconomic models used for such purposes. Finally, a decision must be made by analysts and policymakers to utilise the data in economic analyses. This final step – deciding to use the information – is often overlooked. Much of the wealth accounting world has operated under an 'if we build it, they will come' model. But there is an inertia in economic statistics that favours the status quo. We therefore highlight below several potential avenues for economists to use data on natural capital to better understand mainstream economic questions relating to risk, inequality within and between countries, and productivity.

In the next section we develop a simple model to introduce the risks associated with depletion into the valuation of natural capital assets. The SEEA adopts the SNA convention of using exchange or market prices for valuation purposes, but these differ by definition from the appropriate shadow (or 'accounting') prices in the context of environmental externalities. There is a large and growing literature on appropriate valuation methods (see for example Bateman et al 2002; Atkinson et al 2012; Fenichel and Abbott 2014; Islam et al 2019). Our contribution here, in the context of using natural capital accounts as a tool for forward-thinking, is to provide a simple model to incorporate risk to the assets from degradation or loss. We then turn to three areas of immediate policy interest to suggest how natural capital accounts can shed important light on the nature of the policy challenge and potentially improve outcomes: inequality, productivity, and net zero transition.

II. Incorporating risk in natural capital measurement

The established body of knowledge concerning theories of capital, asset pricing, and risk management can usefully be brought to bear on questions of environmental-economic relevance. Horan et al (2018) posit natural capital as part of a portfolio of assets, noting that efficient portfolio management would require the risk-free return on assets to be equal to the return that could be earned by investing in a numeraire capital stock (for example a tradable AAA-rated government bond with a face value). But in addition to the uncertainties and dynamics that govern conventional asset pricing, natural capital entails non-market capital services, variously encompasses public, quasi-public, and private good characteristics, and is additionally subject to ecological complexities and dynamics – all of which complicate valuation. Here we set out a simple model to begin thinking about how risk might be incorporated into the measurement and valuation of natural capital.

Consider the national statistician tasked with reflecting the value of forest natural capital within the national account. It is one thing to report that a country has 1 million ha of pristine forest, but another thing altogether to know there is a 50% chance it burns within the next 30 years. If we have scientific projections of how natural capital stocks might be at risk, how might this be reflected in a wealth account? We could focus on the return on risk-adjusted capital, noting that the capital stock is at risk but assuming that the returns per unit of forest are constant. Alternatively, we could consider a scenario in which the capital remains intact, but that the value of the ecosystem service flows generated by it are at risk. In this case, the variable of interest is the risk-adjusted return on capital. Finally, we could imagine a scenario where both the capital stock and the ecosystem service flows are at risk, in which case we may be interested in the risk-adjusted return on risk-adjusted capital. The challenge is how might one formalise these issues such that the relevant risks could be reflected within a natural capital account.

We begin by asking how the risk of ecosystem collapse translates into economic risks. We want to derive the adjustment that accountants should make to the value they attribute to ecosystem assets. In our simple model, time is continuous, denoted by $t \geq 0$. Suppose an ecosystem (such as a forest) of size K, yields a *flow* of benefits of P dollars *per unit of forest* to the firm. Forest ecosystems generate a wide range of economically valuable environmental goods and services, including air purification, nutrient cycling, timber production, carbon storage, and as a place for outdoor recreation. P reflects the combined contribution of this suite of services to welfare. But the relevant shadow prices are not readily observed, meaning that in practice, natural capital and ecosystem service accounts rely on estimations and proxies. In addition, UN SEEA guidelines require the use of market-equivalent values within national natural capital accounts for consistency with the SNA. If market data is used as the basis for estimating P, and if the market has already identified, aggregated, and priced in all potential risks to the forest, then adding an additional risk parameter into the model could double count some risk. However, it is unlikely that current market prices fully reflect the risks of ecosystem collapse so we need to suggest how risk could be accounted for.

We begin by assuming P is constant. We will later assume that P increases exponentially, to reflect the idea that natural capital will become increasingly scarce relative to produced capital. The discount rate the firm applies to future benefits from the forest is $r > 0$ per unit of time.

So as long as the ecosystem remains intact, the flow of benefits from it is PK at each moment (in the case where P is constant). If the firm is certain that the ecosystem would remain unblemished forever, it would be worth PK/r. But because ecosystems are being degraded generally, the firm's projection is that its supply source will collapse at an unknown date before T years from now. We study the case where the distribution of this risk is uniform: at $t = 0$, there is a constant probability rate $1/T$ of the ecosystem being destroyed in the interval of time $[0, T]$.

Bayesian updating implies that, conditional on the forest surviving until time t, the probability that it will be destroyed at any date in the interval $[t, T]$ is $1/(T-t)$. Viewed from $t = 0$, the probability that the forest will survive until t, is thus $(T-t)/T$. The *hazard rate* at t is $1/(T-t)$, which goes to infinity as t tends to T. We can now apply this to calculate the risk-adjusted shadow value of the pristine forest.

As the probability that the forest will exist until t is $(T-t)/T$, the expected worth of the ecosystem is:

(1)

$$PK\left(\int_0^T \frac{e^{-rt}(T-t)}{T}dt\right) = \left(\frac{PK}{r}\right)(1-e^{-rT}) - \left(\frac{PK}{T}\right)\left(\int_0^T (te^{-rt})dt\right)$$

Write the risk adjusted value of *K* as a function of *T* as *F*(*T*). Then integrating the final term on the right-hand side to equation (1) by parts yields:

(2)

$$F(T) = \left(\frac{PK}{r}\right)\left(1 - \frac{(1-e^{-rT})}{rT}\right)$$

The risk adjustment term is thus *R*:

(3)

$$R = \left(1 - \frac{(1-e^{-rT})}{rT}\right)$$

It is straightforward to confirm that $dF(T)/dT > 0$. Thus, *F*(*T*) is a monotone increasing function of *T* in the interval [0, ∞). Moreover, $F(T) \rightarrow 0$ as $T \rightarrow 0$ and $F(T) \rightarrow PK/r$ as $T \rightarrow \infty$. Both limits are intuitive. Moreover, the risk-adjustment factor, *R*, lies between 0 and 1, exactly as one would expect.

An extension of the model involves abandoning the assumption that *P* is a constant. With the world's rainforests being razed to the ground to make way for cattle ranches, plantations, and mines, we would expect the benefits from *K* to increase over time relative to our assumed *numeraire*, market income. The simplest assumption is that *P* increases exponentially at rate $\beta > 0$, that is, $P(t) = P(0)e^{\beta t}$. To be concrete, assume $r > \beta$. It is now simple to confirm that:

$$F(T) = \left(\frac{PK}{(r-\beta)}\right)\left(1 - \frac{(1-e^{-(r-\beta)T})}{(r-\beta)}T\right)$$

That is, the risk adjusted shadow price of capital is the *higher* the *larger* is β. That too is exactly what intuition would suggest.

Returning to equation 2, the risk-adjustment in this simple model could be applied either to the shadow price *P* or as an adjustment to the stock, *K*. The result is general and not restricted to the random death process we consider here: the associated risk factor is a number lying between 0 and 1 and can be deployed either on *P* or *K*.

Future work could explore how P might change with income. If income rises through time, then a standard Ramsey decomposition would imply a higher discount rate. If one abstracts the pure rate of time preference and assumes an income elasticity of unity (as is commonly the case) this should be proportionate to growth. This would imply a falling current stock value for the forest in proportion to increased income growth assumptions through time. Of course, if the impact of natural capital loss is non-marginal, say because of the systemic effect of all the forests burning at once, then income may not rise through time and would need to be modelled endogenously in line with the risk of catastrophe.

An important question remains over the potential sign and magnitude of the climate beta.[2] Early investigations asserted that large income losses from extensive warming suggest a higher benefit from mitigation investments, and thus a negative climate beta (Howarth 2003; Weitzman 2007; Sandsmark and Vennemo 2007). In contrast, Nordhaus (2011) indicates that carbon intensive growth and technological progress could deliver greater consumption, emissions, and warming, leading to a greater return on mitigation investments. Thus consumption and mitigation benefits would be positively correlated, yielding a positive climate beta. Dietz et al (2018) use DICE to model climate beta explicitly, finding that upward pressure on β arising from uncertain technical progress dominates downward pressure on β arising from uncertain climate sensitivity and damages. That is, in line with Nordhaus (2011), they find that emission reductions actually increase the aggregate consumption risk borne by future generations (Dietz et al 2018, p260).

Alternatively, rising incomes could lead to increased substitution (say from burning trees for fuel to renewable electricity), or could even change preferences towards greater consideration for natural capital conservation. While evidence suggests that substitutability of natural capital with other forms of capital may be low to moderate (Cohen et al. 2019; Yamaguchi and Managi, 2019), higher income may facilitate a greater access to resources that can help adapt to or mitigate the risks associated with the loss of natural capital. For example, the company may be able to invest in alternative sources of water or energy or use their financial resources to develop new technologies that reduce their reliance on the natural resources stock in the forest. In those cases, under the assumption of a decreasing marginal utility of income, in more rapidly growing economies there will be more income in the future and the negative impact on human welfare will be marginally less (Liu et al. 2010).

Our simple model brings accounting for risks to natural assets into natural capital accounting, which will be needed for a fuller welfare accounting. An advantage of natural capital accounting is that it forces other areas of economic analysis to begin to incorporate previously-omitted but growing environmental risks. Future work could explore systemic risks, highlighting interactions and correlations between natural and other forms of capital.

III. Natural capital accounts and inequality within countries

The Dasgupta Review (2021) laid down the gauntlet for economists to demonstrate how natural capital accounts can shed light on mainstream economic challenges. We consider three ways in which natural capital accounting is relevant to current policy challenges. The first of these concerns the interactions between natural capital, environmental policies and inequality.

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[2] The authors are grateful to Professor Joe Stiglitz for raising this intriguing question.

The credibility and usefulness of natural capital accounts will depend on their ability to improve understanding of the distributional consequences arising on the one hand from changes in natural capital, and on the other hand from environmental policies that aim to preserve natural capital. The distributional aspects are important both within and between countries. Up to a quarter of inclusive national wealth in developing countries consists of natural capital, while in OECD high-income countries it represents around 3% of national wealth. However, the value of natural capital in the latter is three times that of lower income countries (World Bank 2021). The available evidence suggests that of all the asset classes, natural capital is the only one that is in sustained, world-wide decline (Dasgupta 2021, World Bank 2021).

This decline contributes to inequality in at least two ways. First, poor, marginalised, and vulnerable groups may be more directly exposed to the physical risks associated with natural capital depletion: they may be less likely to hold insurance against floods, droughts, and fires; their livelihoods may be more dependent on primary agricultural commodities or even directly dependent on local natural capital for food; and losses in natural capital may constitute a greater proportional loss of total wealth than for higher income groups. We return in the next section to the global distributional question.

Second, lower income and marginalised groups may be more exposed to the negative trade-offs associated with environmental policies that will safeguard nature if, for example, their tools and skills are less transferable in the shift towards a net zero and nature positive economy. By systematically reviewing the outcomes and trade-offs of decarbonisation policies, Peñasco et al (2021) show that while regulatory, economic, and financial policy instruments are generally associated with positive environmental, technological, and innovation outcomes, many policies supporting the deployment of renewable energy are also associated with short- to medium-term negative effects on distributional outcomes. For instance, 12 of the 13 studies they reviewed identified regressive effects from feed-in tariffs, a result that held across 40 geographical contexts for which data was available. Similarly, 63% of studies reviewed found negative distributional impacts from energy taxes.

We can expect that if people perceive environmental policies as a threat to their own income or well-being, public acceptance will be low and the transition to net zero will be impaired. Distributional and economic aspects are at the core of that public acceptance. If decarbonisation policies are perceived to be unfair or lead to job losses, this could delay action, which scientific evidence suggests we cannot afford. A common critique of net zero policies is that they may reduce competitiveness, raise prices, and exacerbate inequalities. But the evidence suggests that unabated climate change already is and will continue to exacerbate existing inequalities within and between countries, and will create new ones.

On the other hand, clean technologies afford opportunities for greater efficiency and productivity in the use of resources. One study suggests that transitioning to a decarbonise energy system by 2050 would save at least $12 trillion globally in comparison to the current scenarios of fossil fuel use (Way et al 2022). How those savings are distributed represents another source of concern. From a political economy perspective, climate and environmental policy implementation and the process of global decarbonisation requires the access to minerals like cobalt, lithium or rare earth among many others whose production is concentrated in few countries, even to a larger extent than oil and gas (IEA, 2021). In this sense inequality and perceived distributional concerns may remain at the core of the energy transition if not considered adequately. Indicators like energy access, energy dependency, energy security or the environmental, biodiversity, and competitiveness effects experienced sites of extraction are indicators that can shed light on the distributional impacts of decarbonisation policy (Newell and Mulvaney, 2013; Mercure et al. 2021).

There are several implications derived from the evaluation of distributional impacts of policies aiming to improve our natural environment. Much of the available evidence has used metrics such as the impacts on income and wealth distribution to analyse the progressive or regressive effects of the implementation of certain types of policies in particular for societal groups such as vulnerable households. Less common, however, is assessment of distributional impacts associated with the possible co-benefits of reducing environmental damage, including for example food security, energy security, or improved physical health (Kortetmäki & Järvelä, 2021); and indeed improved accessibility to natural capital and/or environmental goods (Montenegro et al. 2021). The latter is more difficult to quantify but neglecting this dimension in assessment and evaluation of the impacts of environmental policies can generate myopic results in regards to their effects on inequality of different policies (Montenegro et al. 2021).

A wealth-based approach can shed further light on longer term questions of distribution and inequality. Given the variety of distributional impacts associated with natural capital assets and the policies essential to protect them, an array of indicators will be necessary in two fronts: first, in *ex ante* assessments of the impacts of climate change and the cost-benefit consideration of the adoption of certain environmental policies; and second, in *ex post* evaluations of such impacts, either the co-benefits or trade-offs. These can differentially impact the consumers of the affected goods or services, either those households or firms with different income levels, revenues and/or situated within different regions in one country or in different countries (Montenegro et al. 2021). Some studies have explored the impact on consumers (their spending on energy as a percentage of total expenditure) and the differences in the ability of large and small firms (including renewable energy producers of various sizes) to thrive under a range of policies. Age too is an important yardstick: policies may affect intergenerational equity. Internationally, energy transition may affect countries at different levels of development.

Fuller natural capital accounts would help shed light on the distributional effects across time and space of policies such as land reform or climate action. While great progress has been made in the production of natural capital accounts, in the context of the SEEA-EEA, the resulting accounts are not yet fully delivering on this potential use. Several extensions could be considered. These include natural capital valuation approaches that reflect regional- and asset-specific risks (as set out in Section II) or the use of equity weights designed to reflect within-country differences in access to natural capital and associated ecosystem services such as improved air quality (Bond and Basu, 2021; Mullin et al. 2018; HM Treasury, 2022).

IV. Natural capital and inequality between countries

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 current development challenges deal with the intersection of the benefits of economic activity and the costs of environmental degradation. International trade plays an important role. 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 (Dupuy 2011; Dupuy and Agarwala 2014). Measurement systems that fail to account for this 'offshoring' of natural capital consumption may provide a distorted picture of national and global sustainability and make it harder to address the global collective action problem.

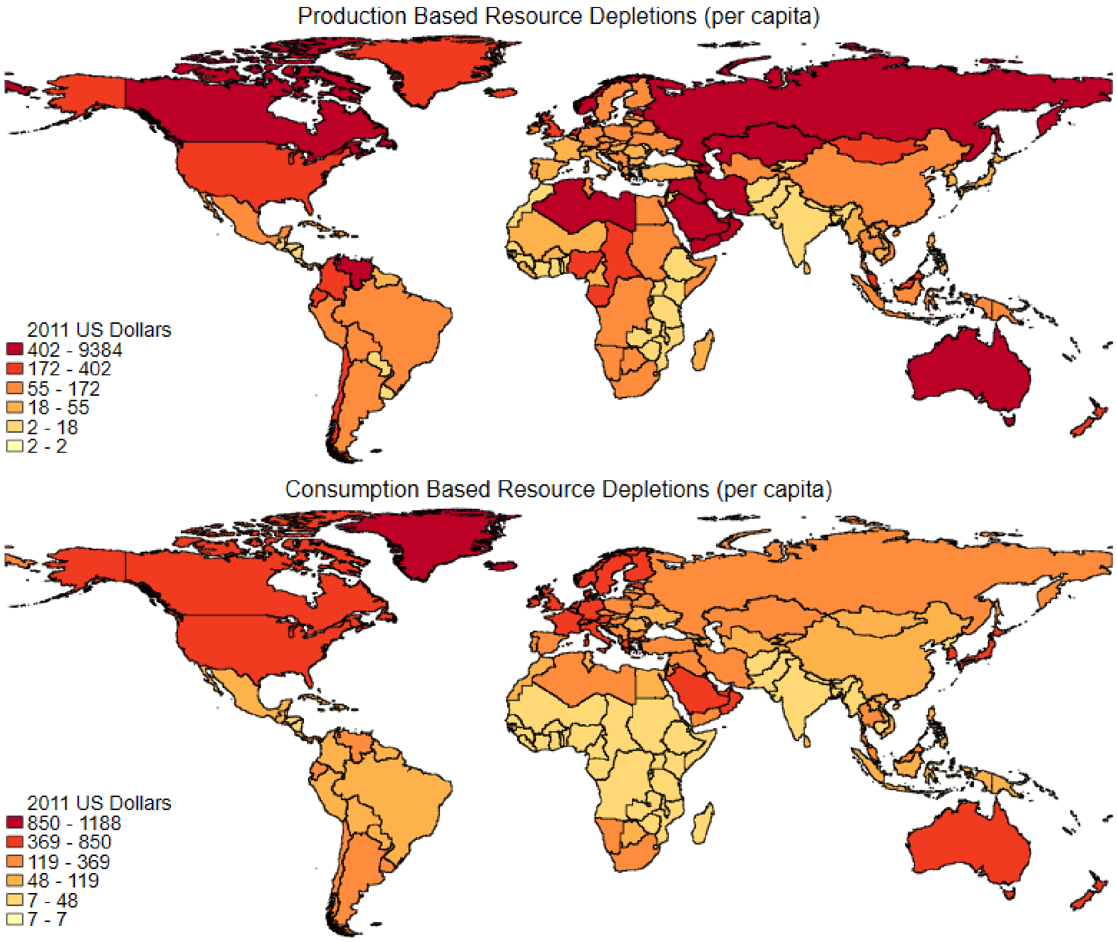
Most wealth accounting efforts employ territorial accounts that describe trends in natural capital stocks within a country's national borders and are therefore relevant for calculating domestic per capita natural capital depletions. Trade enters solely through the effect of net exports on national savings. We argue that because international trade is a large and in general still 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. 2009, p77).

Atkinson et al (2012) and Agarwala (2020) propose the development of 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, 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. The need for consumption-based accounts has been firmly established in the carbon accounting literature, partially to explore various interpretations of 'responsibility' for CO_2 emissions (Davis et al. 2011; Steininger et al. 2016; Afionis et al. 2017). Atkinson et al (2012) and Agarwala (2020) extend this debate to a much wider range of natural capital assets, including oil, coal, gas, minerals, fisheries, and timber. Examining both sets of accounts simultaneously provides a more complete understanding of an economy's impact on both national and global sustainability, provides insight into dependencies on domestic versus global resource stocks, and is crucial to understanding resource security concerns and identifying opportunities for joined-up bilateral and international resource policy.

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) shows that in physical terms, resource extraction increased 1.8-fold from 1980 to 2011, but that resource trade increased by a factor of 2.5 over the same period, indicating the distortion is accelerating.

Using the GTAPv9’s 140 country, 57 sector multi-regional input-output model, Atkinson et al (2012) and Agarwala (2020) compute the value of per capita natural capital depletions across oil, coal, gas, mineral, forestry and fishery resources. Greenhouse gas emissions are not included. 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).[3]

Figure 1 Production and Consumption Accounts for Natural Resource Depletion



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[3] 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.

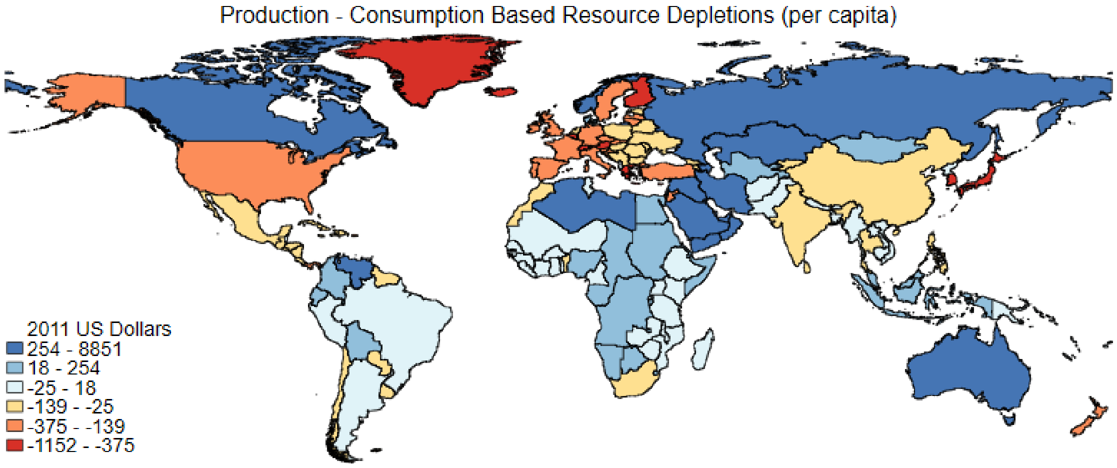
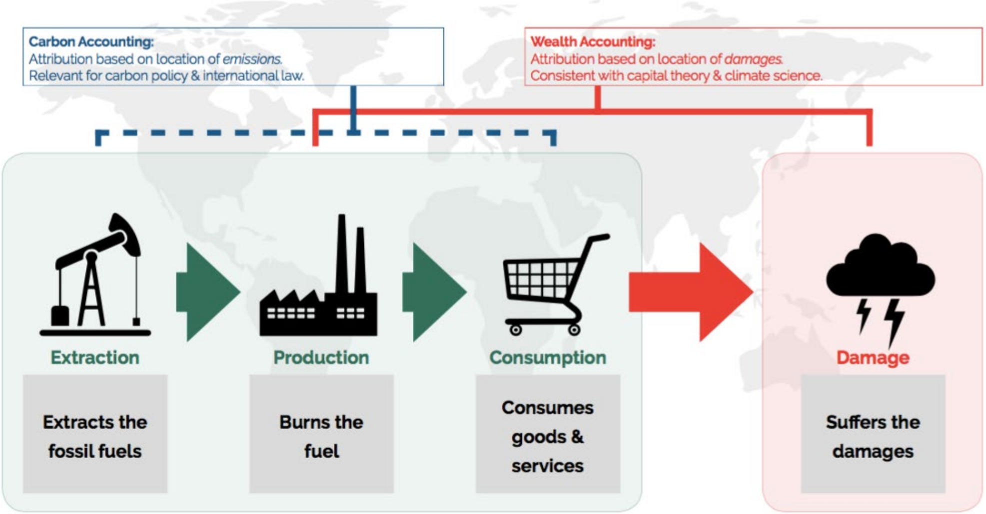


Figure 1a-b show per capita production and consumption-based resource depletions. Fig 1c shows the difference (production minus consumption) in per capita resource depletions. Resources include forestry, fisheries, coal, oil, natural gas, and other mining (metal ores, uranium, gems). Values in 2011 USD.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

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 the 'policy blind spot' (Steininger et al. 2016) that would arise if policies were informed by either the production or consumption account rather than both. Negative (positive) values indicate per capita resource net importers (exporters).

Accounting for natural capital across borders becomes even more important when we consider global public goods with transnational externalities. We know that greenhouse gases reduce wealth, but the question remains, *whose?* Consider the following sequence: coal extracted in Malaysia is burned in China to produce goods that are consumed in the UK. The associated climate change increases extreme weather, reducing productive capacity in Bangladesh. What happens to inclusive wealth along this chain of events? Accounts have been developed that attribute the carbon externality at various points along the supply chain: the country of extraction, combustion, or final demand Davis et al (2011). But this ignores a critical step: the country in which the damages are ultimately realised, see Figure 2.

Figure 2. From carbon accounting to wealth accounting across borders.



Source: Agarwala (2020).

In practice, carbon and natural capital accounting procedures deduct the value of emissions from the country in which they are released. But for the theory of inclusive wealth, this would be appropriate only under the restrictive and scientifically unrealistic condition that climate externality exactly coincided with the location of emissions. Arrow et al (2012) show that in the presence of transboundary externalities, the appropriate adjustment to each nation's wealth would reflect the domestic damages generated by global emissions rather than the emissions generated domestically. Returning to our example, this means measured wealth in Bangladesh would fall owing to decisions taken in Malaysia, China, and the UK. This is unfair, but in the absence of international compensation for greenhouse gas emissions, provides a far more accurate depiction of the relationship between emissions and domestic versus global sustainability. Damage-based accounts require country-level estimates of the climate impacts arising from the marginal ton of greenhouse gas emissions. This remains an important obstacle, but initial progress shows that integrated assessment models and increasingly, macroeconometric climate models can be used (Arrow et al 2012; UNU-IHDP 2012; Agarwala 2020). In theory, damage-based accounts could be constructed wherever countries impose externalities upon each other through their management of global public goods, but the complexity of the measurement and valuation challenges will vary across types of natural capital.

Constructing natural capital accounts from production-, consumption-, and damage-based perspectives reveals different, yet equally important, trends in natural capital depletion. 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. Production, consumption and damage accounts are useful complementary tools for understanding the natural capital impacts and dependencies of nations.

V. Natural Capital Accounts and Productivity Measurement

A major challenge faced by many economies is the slowdown in productivity growth since the mid-2000s. Compared to the prior long-run trend, this growth slowdown accounts for an output shortfall totalling around 20% of GDP depending on the country.

One obstacle to enacting policies to combat climate change and protect natural capital is that they are often perceived reduce growth and productivity. This perception has been challenged (see section VI below). One problem is that the standard approach to measuring productivity adopts a private goods perspective, permitting by assumption the 'free disposal' of bad outputs. But if production activities generate externalities, then relying on market-based measures of output will distort the measurement of productivity. The development of environmentally-adjusted measures of national income is not new (Nordhaus and Tobin 1973; Repetto et al 1996; Muller 2014), but the exercise here is to show how these can inform mainstream policy issues such as productivity growth.

Viewed against the backdrop of climate change, the exclusion *by assumption* of carbon emissions from productivity analyses is hard to defend. To investigate the relationship between productivity growth and natural capital, Agarwala and Martin (2022) utilise the richness of UK natural capital and sectoral production data to construct environmentally-adjusted productivity measures for the UK, deducting the value of greenhouse gas and air pollution emissions from the value of output. As in Muller (2014), they focus on greenhouse gas and air pollutant emissions because of the availability of high quality emissions data, the high economic impact of greenhouse gas and pollution emissions, and the ability to directly attribute emissions to economic activities within the national accounts. Extending beyond the calculation of a 'green GDP' measure, they use this adjusted-GVA to calculate environmentally-adjusted labour productivity measures. Emissions prices are taken from UK government documentation and are reflected in Table 1.[4]

Table 1. Summary of emissions and pollutants, including data sources

Category	**Type**	**Price data source**	**Price per tonne in base year**	**Assumed price growth per year**	**Total fall in volume 1990-2019**
Greenhouse gases	All	BEIS	£241 (2020)	1.5%	41%
Acid rain precursors	Nitrogen oxide (NO_x)	Defra	£6,383 (2017)	2%	67%
	Sulphur dioxide (SO_2)	Defra	£13,206 (2017)	2%	95%
	Ammonia (NH_3)	Defra	£7,923 (2017)	2%	17%

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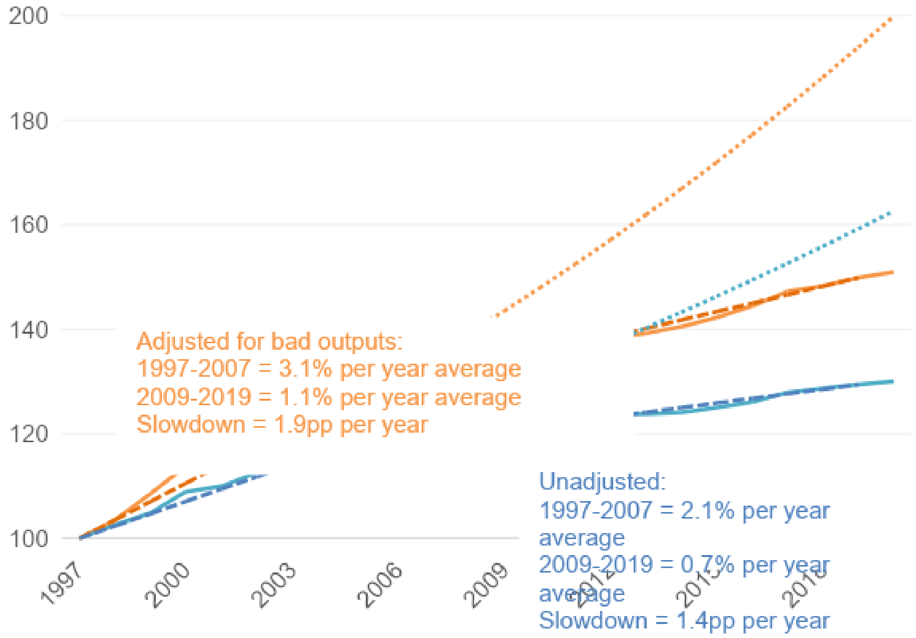
[4] The UK Department for Business, Energy, and Industrial Strategy (BEIS) adopts a 'target-consistent' carbon price rather than a social cost of carbon. This is partially due to the difficulties of estimating the SCC. Rather than estimating the SCC, the marginal abatement cost approach relies on government to set a policy target such as reaching net zero emissions by 2050, and then estimating the cost of achieving it. There are still uncertainties – around changing targets, the availability of abatement technologies, and their costs, but proponents of this approach argue that such uncertainties are far smaller than those encountered in estimating the SCC (Dietz and Fankhauser 2010; Stern and Stiglitz 2021)

Other pollutants	Non-methane volatile organic compounds	Defra	£102 (2017)	2%	68%
	Particulate matter (PM2.5)	Defra	£73,403 (2017)	2%	78%

Source: Agarwala and Martin (2022).

GVA was adjusted downwards by deducting the product of the relevant prices and quantities. This drove some industries (manufacturing of coke and petroleum products and air transport) to post net negative GVA for the entire assessment period. However, most industries saw faster productivity growth after adjusting for bad outputs, reflecting reductions over time in per unit emissions. At the aggregate scale, environmentally-adjusted labour productivity growth was higher (See Figure 3).

Figure 3. Whole economy labour productivity, with and without adjustment for bad outputs, with pre-GFC-downturn trends, 1997 to 2020



Notes: Pre-Great Financial Crash-downturn trend calculated as the compound average annual growth rate from 1997 to 2007. Projection assumes this rate of growth continues from 2007 onwards.

The general result that environmentally-adjusted productivity growth will be higher than conventionally-measured productivity growth can be expected to hold in countries where the emissions intensity of output has been falling over time (Muller 2020; Agarwala and Martin 2022). However, the opposite can be expected in countries where the emissions intensity of output has risen (Mohan et al, 2020). There are some important limitations to the case studies presented here. Focusing on production-based emissions ignores leakage and offshoring effects and future work should encompass multi-regional input-output analysis to reflect this. At least as important is the fact that household production falls outside the production boundary, so their results based on GDP-adjustment exclude energy use and associated emissions by consumers (for example in personal transport and home heating).

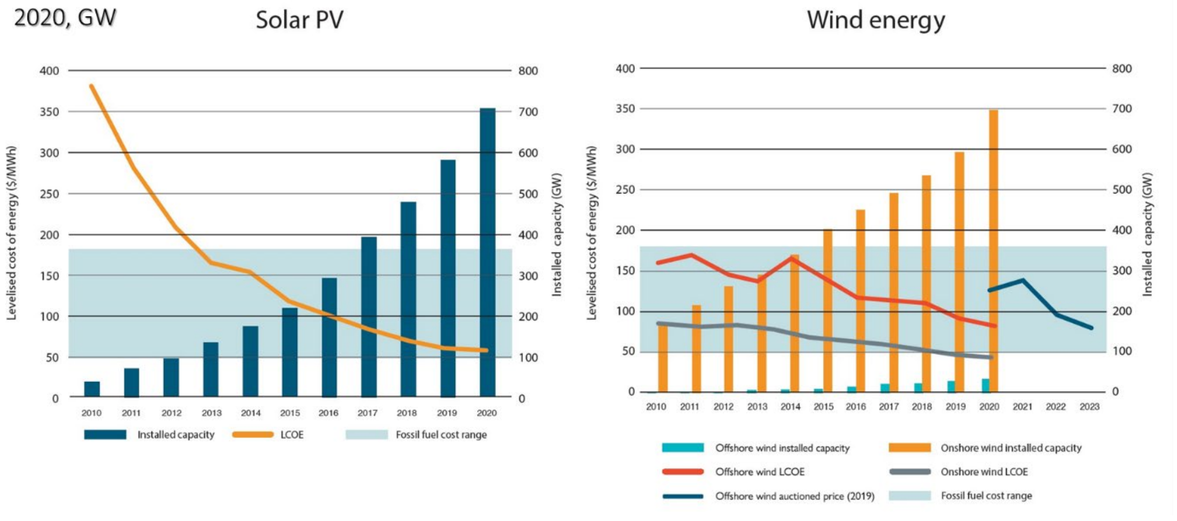
Whilst this aligns their results more closely with mainstream economic statistics, these are clearly important omissions that future work should seek to address. Such extensions will require, and are made possible by, the regular publication of natural capital accounts with sufficient sectoral detail.

VI Natural Capital and Macro Transition Policies

Measurement of natural capital will create a clearer picture of the scale and pace of the depletion of natural assets and the flow of services they provide to current economic activity. At the same time, the policy and behavioural responses to resource loss and climate change will affect the valuation of all assets. The shadow prices of natural assets should fall (sometimes dramatically) and their productivity in generating ecosystem services should increase. For instance, the transition to a low-carbon production system risks devaluing or stranding physical, human and knowledge capital. Wealth accounts including natural capital will provide decision-makers with a clearer picture of the implications of transition policies and their potential to rapidly impact the value of assets.

Historically, economic assessments of the cost and deployment of decarbonisation technologies have been pessimistic relative to experience in key sectors such as renewables, electric vehicle and battery storage (Grubb et al 2021). The large gap between projected costs and realised costs suggests that the models being used are not adequate. By ignoring path dependencies in innovation, the cumulative nature of innovation processes, learning-by-doing, and economies of scale in production, distribution and discovery, as well as the role of government in crowding-in private investment, such assessments failed to predict the rapid cost reductions witnessed in renewables generation and battery technologies. Figure 4 shows the strong inverse relationship between deployment and clean technology costs.

Figure 4: The deployment and cost of renewables.



Source: Grubb et al. 2021.

Conventional analyses that ignore these effects, or treat them as exogenous to the model, generally overstate the cost of climate action, leading to costly policy delay (Penasco et al. 2021; Grubb et al. 2021). Indeed, delay can itself increase overall decarbonisation costs, by postponing the reinforcing feedbacks between deployment and cost-reductions, making high cost estimates potentially self-fulfilling (van der Meijden and Smulders 2017).

Economic models need to encompass the self-reinforcing role of expectations and strategic complementarities, whereby the pay-off for policymakers, businesses and consumers from investing in clean technologies, institutions and behaviours is a function of how many others do likewise. In the longer run, such feedbacks increasingly give new technologies the advantage over incumbents. Commodity-based systems, such as fossil fuels, are subject to diminishing returns to scale, and hence have limited scope for operational costs to fall as demand rises. The cheapest resources to extract and transport are harvested first. By contrast, new technologies are characterised by powerful economies of scale, both in discovery and production costs (Geels et al. 2021).

Acemoglu et al. (2012) build on this understanding to make a powerful theoretical case to suggest that policy to support clean innovation can be temporary. Once the “clean innovation machine” has been “switched on and is running,” it can be more innovative and productive than the conventional alternative, with a positive impact on GDP levels and growth. For example, renewable energy generation is already cheaper than incumbent energy technologies (Way et al 2022). This strongly indicates that economic modelling to inform policy choices needs to move beyond single equilibrium constraints, focusing on static allocative efficiency, to understand the processes which generate dynamic efficiency and multiple equilibria. Capturing and incorporating reinforcing or dampening feedbacks, allows modelers to better assess the risk of changing asset valuation alongside the creation of entire new markets and new assets (Aghion et al., 2014). Natural capital accounts are a complementary tool to this dynamic (non-convex, non-marginal and endogenous) systems approach. They help track the large impacts of interventions on valuations.

Natural capital and wealth accounts are more broadly useful for assessing and guiding macroeconomic policies (Agarwala and Zenghelis 2020). Fiscal sustainability requires investing in assets that generate sustainable private and public returns. If public borrowing is used to invest in the productivity of public assets (Buiter et al., 2020), or to enable private assets to become more productive, it can generate growth and tax revenues that allow debt interest to be repaid (Robins et al., 2020, Agarwala et al., 2021). This means investing in complementary assets that raise productivity and offer the greatest potential (Aghion et al., 2016) in the carbon-constrained markets of the future.

For example, it requires investment in human capital, to secure the skills and jobs, and, through R&D to drive the technologies, processes and institutions necessary to support the clean economy, intangible capital. By the same token, as part of a comprehensive wealth approach, natural capital accounts can guide investment in assets that are likely to become devalued or stranded. Such macro considerations indicate the need to adopt a broader balance sheet perspective. The inclusive wealth approach to measuring the comprehensive range of assets in which the public and private sectors invest, generates a better understanding of the impact of policies and thereby helps inform policy choice at a time of rapid, non-marginal structural change (Zenghelis, Agarwala et al., 2021).

VII Conclusion

The origin and purpose of national statistics was to provide a clear view of the evolution of the economy, in order that governments and other decision makers could make good choices. The original SNA framework was suited to this purpose in the seemingly resource-abundant postwar world. The definitions and standards have continued to evolve during subsequent decades and are currently undergoing another major revision, due to be published in 2025. This will include recognition of the need to measure natural capital, and some other assets in inclusive wealth. We have argued that while welcome, there is a significant challenge ahead, in going beyond the SEEA's use of exchange prices in order to get closer to 'true' shadow prices, including adjusting for risk to natural assets; and in the magnitude of the data collection needed. However, we have also shown how natural capital accounts can be used to address better some of the policy challenges facing the economy: inequality, productivity slowdown, and the opportunities and risks of the net zero transition.

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[to be completed and checked]

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