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Natural Capital and Wealth Accounting for Sustainability Assessment: A Global Perspective

Rintaro Yamaguchi[1], Moinul Islam[2] and Shunsuke Managi[3]*

[1]*National Institute for Environmental Studies (NIES), 16-2 Onogawa, Tsukuba 305-8506, Japan; ORCID: 0000-0002-0470-1483; yamaguchi.rintaro.r41@kyoto-u.jp*
[2]*Kochi University of Technology, Kochi, Japan; moinul.eco@gmail.com; ORCID: 0000-0002-0309-3156*
[3]*Urban Institute, Kyushu University, Fukuoka, Japan; managi@doc.kyushu-u.ac.jp; ORCID: 0000-0001-7883-1427*

ABSTRACT

Capital assets provide a wide variety of benefits and services to current and future generations. If intergenerational well-being is governed by capital assets, then they should not decline. This is the simple intuition behind nondeclining capital assets as an indicator of sustainability. We review recent developments in the wealth-accounting literature, with a particular focus on global natural capital. Aiming toward climate and biodiversity targets in economies constrained by carbon budgets and planetary boundaries, the wealth index needs to be updated to reflect global scarcities. Inclusive wealth of United Nations and the *Dasgupta Review*'s focus on the conceptual tools of impact inequality, as well as the safe operating space approach, might give us some toolkits to make these changes. Other challenges include spatial and global aggregation and the upscaling of micro to macro. This also calls for utilizing the wealth index for cost-effectiveness, as well as cost-benefit, analysis. Looking at another focus

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*Corresponding author.

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of the inclusive wealth and *Dasgupta Review*, we touch on the effect of population change on per capita wealth and measurements of well-being in the context of an ever more densely populated planet. Finally, we also discuss that more empirical research is expected to revise approaches to the comprehensive net national product, as well as to wealth accounting.

Keywords: Inclusive wealth; wealth accounting; genuine savings; sustainable development; natural capital; comprehensive NNP

JEL Codes: D63, O41, Q01

1 Introduction

Gross domestic product (GDP) and its variants have continued to be the most familiar and well-known indicator of the economic progress of nations. Since its inception, the divide between what GDP can express and people's well-being has been widely debated. Along with the conventional challenges and the absence of a measure of subjective well-being, Stiglitz *et al.* (2010) added in a well-known review the GDP's inability to indicate sustainability.

To see how GDP fails to capture sustainability, imagine an economy that depends on forests that provide both timber harvesting and forest ecosystem amenity services. Resource rents from timber harvesting — i.e., revenues net of harvesting costs — are recorded as production in national accounting, but the erosion of the productive capacity of the forest is not captured. Over time, GDP may grow with the input of forest resources, but if harvesting overwhelms the regenerative capacity of forests, then we gradually deplete the forest capital until we suddenly come to a dead end. Not only do we face classic resource exhaustion, but we also lose all the ecosystem services of forests, including flood control, pollutant removal, climate regulation, and cultural services. Having different objectives, GDP cannot enable us to trace the long-term movement of well-being, let alone such a one-two punch. The canonical example just illustrated also shows how to fix the current national accounting: just include the value of any capital asset that is expected to contribute to the well-being of current and future people.[1] The adjective "any" lives in the spirit of qualifiers such as *genuine* savings, *inclusive* or *comprehensive* wealth accounting, and *comprehensive* or *green* net national product (NNP). The change in the real value of (or the nominal value of the change of) produced, human, and natural capital assets should demonstrate the change in intergenerational well-being, an indicator of long-term sustainability.

In practical accounting, progress has been made in two approaches. The first is to expand the System of National Accounts (SNA) to include the contributions from ecosystem services. Such an expanded System of Environmental-Economic Accounting (SEEA) has just been officially approved in the United Nations *et al.* (2021). The second is to directly focus on measuring the value of (the change in) capital assets (i.e., wealth). Both approaches are complementary rather than substitutable. In fact, we will argue that another hybrid approach also shows promise, which is to adjust GDP to obtain a comprehensive NNP that reflects the value of the increase and decrease in capital assets.[2] Currently, there are notable differences between SEEA and wealth accounting approaches. For one thing, the SEEA uses exchange values as a natural extension of SNA, while natural capital and wealth accounting expresses the state of capital assets using its shadow values (i.e., consequences in welfare or well-being terms) (Hein *et al.*, 2020; Obst *et al.*, 2016). Marginal shadow pricing is typically used in wealth accounting, but average shadow pricing in the sense of the SEEA can also be used for wealth accounting (Hamilton, 2016).

In particular, ecosystem services and natural capital look at different aspects of the same object: ecosystem services are flow incomes from natural capital stocks. By analogy with capital asset pricing, this means that the price of natural capital should consist of (ecosystem service)

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[1] Here, we are implicitly assuming that the underlying well-being function only covers that of human beings. This could be debatable, given an increasing attention to animal welfare and nonanthropocentric viewpoints. Moreover, the recent concept of "nature's contribution to people" and its converse "people's contribution to nature" might support the nonanthropocentric perspective.

[2] Throughout the paper, we assume closed economies, where GDP (NDP) and GNP (NNP) do not make any difference. We use GDP and NNP because they are most commonly used expressions.

income gain and (natural) capital gain terms, using the appropriate discount rate. Some recent papers delve into this promising microfoundation of natural capital shadow pricing (Fenichel *et al.*, 2018; Rouhi Rad *et al.*, 2021).

As there are already several reviews that have been around for some time (Aronsson and Löfgren, 2010; Arrow *et al.*, 2012; Dasgupta, 2009; Fenichel *et al.*, 2018; Hanley *et al.*, 2015; Heal and Kriström, 2005; Irwin *et al.*, 2016; Managi, 2016; Polasky *et al.*, 2015; Weitzman, 2003; Yamaguchi *et al.*, 2019), in this article, we focus on recent developments and challenges. In particular, we are concerned with a global perspective,[3] given the recent contribution of *The Economics of Biodiversity: The Dasgupta Review* (Dasgupta, 2021) coming from inclusive wealth report (UNEP, 2022), as well as the safe operating space (SOS) approach taken by Barbier and Burgess (2019). Neither is our objective to give an exhaustive review of natural capital research (Islam *et al.*, 2019; Polasky and Daily, 2021), which is bursting and thus impossible to cover in one paper. We focus on the part and parcel of natural capital research that can be placed and integrated as part of inclusive wealth accounting.

In the next section, we describe a simple wealth accounting framework. In Section 3, we focus on the *Economics of Biodiversity: The Dasgupta Review* and the SOS approach to global sustainability, as opposed to local wealth-based sustainability. This leads us to Section 4, where we discuss policy evaluation using wealth measurement. In Section 5, we see some recent developments in natural capital accounting: gray, green, blue, wild natural capital, and renewable energy capital (REC). Section 6 addresses the treatment of the population, another highlight of the *Review*. Section 7 concludes with a future outlook.

2 Framework

Progress has been made in building on the basic theoretical framework of the long-standing literature of green and comprehensive wealth accounting (e.g., Arrow *et al.*, 2012; Asheim and Weitzman, 2001; Dasgupta

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[3] There are some case studies that apply the wealth accounting framework to specific nations (e.g., Islam and Managi, 2019; UNEP, 2021). The framework generally requires more detailed, high-resolution data to obtain more local implications than it does in global comparisons.

and Mäler, 2000; Hamilton and Clemens, 1999; Weitzman, 1976). The underlying idea is intuitive and straightforward: preserving intact the aggregate of produced, human, and natural capital for the well-being of future generations. Dasgupta (2021) calls it the equivalence theorem between (inclusive or comprehensive) wealth and well-being: they move in the same direction (Chapter 13). It should be noted here that we have the equivalence between wealth change and well-being change if and only if we have constant capital shadow prices, as shown later. To make this mechanism work, relevant but often unaddressed capital assets have to be incorporated into wealth.

In a world with a constant population, we suppose that social or intergenerational well-being can be written as discounted utilitarian welfare:

$$V(t) = \int_t^\infty U(C(\tau))e^{-\delta(\tau-t)}d\tau, \tag{1}$$

where utility $U(C(\tau))$ is an argument of consumption in a large sense. Utility exhibits the usual property of diminishing marginal utility. The social discount rate applied to utility is $\delta > 0$, implying that the whole framework is based on discounted utilitarianism, although there are some studies that propose otherwise (Cairns, 2013). In one interpretation of WCED (1987), sustainable development is considered to require nondeclining $V(t)$ over time. We consider a certain resource allocation mechanism (RAM) that maps initial capital stocks to subsequent consumption and investment. If consumption is affected by a relevant set of capital assets in the economy — produced, human, and natural capital denoted as K, H, and N — then, on the one hand, social well-being defined in (1) can be rewritten as the following value function:

$$V(K(t), H(t), N(t), t) = \int_t^\infty U(C(K(t), H(t), N(t), t), \tau)e^{-\delta(\tau-t)}d\tau. \tag{2}$$

On the other hand, one can define wealth W (the sum of the value of these capital assets) as a linear index of social well-being:

$$W(K(t), H(t), N(t), t) = p_K K + p_H H + p_N N \tag{3}$$

where the shadow prices of produced, human, and natural capital can be defined by

$$p_K := \frac{\partial V}{\partial K}, \quad p_H := \frac{\partial V}{\partial H}, \quad p_N := \frac{\partial V}{\partial N}, \tag{4}$$

Shadow prices embody many implications: they represent their own relative scarcity and marginal rate of substitution between capital assets both at the instant and across time, among others (Dasgupta, 2009). It is worth stressing that the value of capital assets per se does not say much about sustainability; what matters is the value of the change in capital assets. It follows that the time derivative of wealth becomes:

$$\begin{aligned}&\frac{d}{dt}W(K(t),H(t),N(t),t)\\&\qquad = p_K\dot{K}+p_H\dot{H}+p_N\dot{N}+\dot{p}_K K+\dot{p}_H H+\dot{p}_N N \qquad (5)\end{aligned}$$

as the shadow prices might not necessarily be constant. If we further assume constant shadow prices during the studied period, or equivalently, if the underlying RAM is autonomous so that $\frac{\partial V}{\partial t}=0$, then wealth and well-being should move in the same direction:

$$\frac{d}{dt}W(K(t),H(t),N(t),t)=\frac{d}{dt}V(t)=p_K\dot{K}+p_H\dot{H}+p_N\dot{N}. \qquad (6)$$

Furthermore, taking the time derivative of both sides of Eq. (1), it follows that

$$\frac{d}{dt}V(t)=\delta V-U, \qquad (7)$$

implying that nondeclining social well-being means current utility is not exceeding the return on social-well-being. Combining Eqs. (6) and (7), we obtain:

$$\delta V=U+p_K\dot{K}+p_H\dot{H}+p_N\dot{N}=:\mathcal{H}. \qquad (8)$$

This says that the current value Hamiltonian, $\mathcal{H}$, which is the sum of instantaneous utility and the value of net investments in capital assets, is equal to the return on social well-being. Since the current value Hamiltonian is frequently interpreted as comprehensive NNP in utility terms, the welfare significance of NNP has been fiercely debated.

There are two different interpretations of the welfare significance of NNP. First, since NNP in utility terms can be expressed as $NNP := U'(C)C+p_K\dot{K}+p_H\dot{H}+p_N\dot{N}$, from Eq. (6), well-being is increasing if and only if NNP is larger than the marginal value of consumption, $U'(C)C$. This assessment looks less straightforward than directly computing the value of the change in wealth (Eq. (6)).

In the second interpretation, NNP might be directly linked with well-being. As shown in Eq. (8), it is the current value Hamiltonian that is proportional to social well-being. If we can connect NNP in utility terms with the current value Hamiltonian by estimating consumer welfare, then higher NNP means higher social well-being. Unfortunately, there does not seem to be agreement that such a gap can be easily filled by some approximation. However, as Asheim and Weitzman (2001) show, the *change* in NNP moves in the same direction as the *change* in social well-being, provided that NNP is measured using proper shadow prices, and in particular, Divisia measures of real *consumption* prices. In the remainder of this article, we focus on the fact that the *change* in wealth also moves in the same direction as the *change* in social well-being, provided that wealth is measured using proper *capital* shadow prices, because to date the available empirical evidence is concentrated on wealth.

There are several global studies that compare the sustainability of nations. For example, the UNEP approach demonstrates that the inclusive wealth of nations overall is growing much slower than the GDP, while most nations belong to the category of "drawing down natural capital to increase overall wealth". What is worse is that a smaller number of countries have depleted both natural capital and wealth, violating both weak and strong sustainability criteria. Globally, the most alarming per capita natural capital growth status shows a 34% decline from 1990 to 2014.

3 Global Natural Capital

The *Dasgupta Review* (Dasgupta, 2021) turned out to be an overarching publication that goes well beyond the subfield of biodiversity. The *Review* has been both welcomed (Groom and Turk, 2021; Priyadarshini *et al.*, 2022) and critically reviewed (Spash and Hache, 2022).[4] There are several recurring punchlines, one of which is what the *Review* calls (global) impact inequality. Impact inequality is a back-to-basics representation in which the impact of human activities on natural

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[4] See also the recent Special Issue: The Economics of Biodiversity: Building on the *Dasgupta Review* in *Environmental and Resource Economics*, for policy discussions that complement the *Review*.

capital services far exceeds their supply. In particular, the *Review* uses the global footprint network (GFN) (2019) study to demonstrate that population times per capita affluence, adjusted for the conversion efficiency, is approximately 1.7 times the supply of natural capital services, which is an obvious sign of unsustainability. We tend to think of development in per capita terms, but it is still the total population that matters in regard to the human impact on global natural capital, which we shall return to in Section 6.

The *Review* also points out that overusing provisioning services degrades natural capital, which in turn reduces not only provisioning but also regulating and maintenance services. The formal model of the *Review* is thus explicit about the population pressure and competing services from natural capital, which enhances our model described in the previous section by adding population and knowledge capital. Knowledge in turn works as an exogenous factor to improve productivity and to reduce our demand on nature.

One of the most salient features of the *Review* is that the economy is embedded in nature, which is captured by the multiplication of nature and the economic output, instead of the economic output as a function of nature. Consequently, if nature should collapse, then the economy becomes an endgame. This setting makes the analytical traction of the macroeconomic model more awkward, so it remains to be seen whether it will be accepted in the mainstream macroeconomics literature. However, the *Review*'s model vividly captures where we are now. Based on these modeling exercises, the *Review* attempts to spread the following messages across a large audience:

- Ensuring that our demands on nature do not exceed its supply and that we increase nature's supply relative to its current level.
- Changing our measures of economic success to guide us onto a more sustainable path.

The *Review* also called for enhancing institutions, especially in the education and finance sectors, to achieve these two goals. The two messages of global impact inequality and inclusive wealth, however, correspond to global and national perspectives, which need to be addressed consistently. In particular, national sustainability in the sense of non-declining inclusive wealth does not ensure global sustainability as measured by our demand for nature and our ecological footprint. In other words, the aggregation of national sustainability might end up crossing the line of global sustainability; in fact, we have already crossed this threshold according to the analysis of the GFN (2019). Natural capital shadow pricing, or inclusive wealth accounting on the whole for that matter, thus needs to be updated to reflect global scarcity and sustainability.

There could be several ways to address this local–global divide. One is of course to enhance shadow prices of natural and other capital assets that reflect risk, uncertainty, irreversibility, complementarity, substitutability, thresholds, and other possible nonlinear drivers. This is a tall order, but possibly nonlinear shadow pricing that is sensitive both to time and to space could be a step in the right direction. In making the shadow price as a function of all the relevant capital assets, inclusive wealth accounting could actually express strong sustainability (Fenichel *et al.*, 2018). Endogenous capital gain might arise as a consequence of making the shadow price an explicit function of capital and time (Arrow *et al.*, 2012; Hamilton and Ruta, 2009). If the underlying shadow price function is nonlinear, then using the simple average shadow price might not necessarily express the true change in well-being (Fenichel *et al.*, 2016). This poses a challenge to natural capital accounting at a national level, most of which is currently based on the assumption of constant shadow prices.

The second way to fill the local–global gap is the aggregation of natural capital across nations to see its consistency with a global wealth metric of some kind. Both UNEP and World Bank publications show the bottom line figure of world wealth as a simple sum of national capital assets (Managi and Kumar, 2018; World Bank, 2021). There could be some interactions, however, between nations by international trade or simply spatial spillovers of capital assets, so forward-looking terms could enter genuine savings (Van der Ploeg, 2011; Yamaguchi, 2021). Moreover, the presence of income heterogeneity across nations could make simple aggregation of natural capital problematic (Baumgärtner *et al.*, 2017; Meya *et al.*, 2020). Both the physical quantity and economic value of ecosystem income flow might be spatially heterogeneous and exhibit spatial decay (Meya, 2020; Yamaguchi and Shah, 2020). Although not necessarily debated in this context, the use of equity weighting would complicate shadow pricing across nations. Leaving these issues aside, what we could do at least for now seems to be to put all three, local, national, and global, natural capital trackers on a dashboard.

The third way to address the scale gap is to consider yet another class of capital asset. A clue can be found in Dasgupta (2021), which includes knowledge capital that affects the efficiency with which products and services from natural capital are put to use. Put in the global natural capital context, knowledge capital might work as a proxy for the extent of our advancements in natural capital use.

In another direction, a new class of capital asset can be applied to SOS, as suggested by Barbier and Burgess (2017a,b, 2019, 2021). If there remains a distance to the planetary boundary of supporting life from where we are, that distance can be a proxy for our operating space. This framework fits an economist's mind, as SOS can work like a classic exhaustible resource. Barbier and Burgess (2017a, 2019) apply this framework to the carbon budget and global forest constraints, respectively, and show increasing shadow price schedules of SOS. Moreover, the optimal vs. actual imperfect depletion of SOS can be compared, where shadow prices for the latter might be more useful for practical accounting.

The authors apply the SOS approach to socioeconomic and environmental targets politically agreed upon and declared as UN SDGs (Barbier and Burgess, 2019, 2021). The approach enables us to compare and trade off goals and targets in different areas and boundaries. In doing so, complementarity and substitution need to be reflected, ideally in their shadow prices (Cohen *et al.*, 2019; Randall, 2021).

To the extent that it measures the distance from the current state to the planetary boundary, the SOS approach is much related to the concept of resilience. In a lead article of a special issue on resilience, Perrings (2006) notes that two ecological attributes of a system have been found to affect its resilience: adaptive capacity and robustness. Adaptive capacity is related to the extent to which a system can be altered without losing the ability to recover and is thus related to the diversity of the system. It is “all about changing in order not to be changed” (Walker, 2020). Robustness, by contrast, is related to the extent to which a system can accommodate perturbations without additional adaptation or alteration and is thus related to the size of a perturbation needed to shift a system from its stability domain (Holling, 1973). The SOS approach therefore seems to particularly relate to the robustness attribute of resilience. In fact, some earlier studies measure resilience as another form of capital stock at a local level (Walker *et al.*, 2010). Looking ahead, incorporating the adaptive capacity aspect of resilience would be more challenging, as it would probably involve the (co)evolution of the underlying RAM (e.g., behavioral response; institutional change).

This brings us to the question of where we would like to put a boundary, or more generally a reference point, of the level of natural capital that we would like to refrain from crossing. Planetary boundaries can be determined to a certain extent by findings of natural science, but they should also depend on how much we would be willing to trade off natural capital with other capital assets and future possibilities.

The reference point is also crucial in defining how much we owe to the Earth and future generations. This environmental debt can be considered a capital asset that enters the liability side of the balance sheet of nations. In wealth accounting, it should constitute a capital asset with a negative sign, as we can speculate that its marginal shadow price is made up of the net present value of the sum of future conservation and damage cost flows. For example, Azar and Holmberg (1995) define generational environmental debt as the sum of the cost of restoration and the remaining cost of damage. They calculate carbon debt as the value of the accumulated carbon stock with a reference point set at the preindustrial level. If the global community defines global mitigation debt as the marginal shadow price multiplied by the difference between the current atmospheric concentration (400 ppm) and the preindustrial concentration (280 ppm), then we should account for this gap as a stock (120 ppm) whose marginal value has a negative sign, in addition to the current climate change damage that is already recorded in wealth accounting. In yet another example, Maher *et al.* (2020) account for the expected decline in wildlife population as a conservation debt measured by the change in value, with a reference point being the current wildlife stock. In either case, mitigation or conservation debt represents a decline in well-being due to future mitigation or damage compared to the reference point.

4 Policy Evaluation: Cost-benefit and Cost-effectiveness Approaches

The two approaches to global natural capital we have seen bring us to several important questions in the largely unexplored arena of policy evaluation. Both the *Dasgupta Review* and SOS approaches can be a response to imminent global natural capital scarcity and the encroachment of planetary boundaries. Moreover, they have in mind some clear lines, if not thresholds, of natural capital, across which we are in the realm of unsustainability in some sense. This is what has been stressed in ecological economics and strong sustainability indicators put forward by Daly (2020), among others, but in principle these limits could be addressed in an inclusive wealth framework as well if proper shadow prices are used (Fenichel *et al.*, 2018). The *Review* and GFN (2019) look to the Earth's capacity — which we have already crossed — while the SOS approach studies the remaining buffer zone as a capital stock. Therefore, the reference lines are either ahead of us or at our back.

If the reference line has been crossed already, we need to push ourselves back to mitigate human impact, by say, reducing our ecological footprint to 1 earth equivalent so that our global resource demand can be within the Earth's capacity for regeneration (Dasgupta, 2021) or paying back our conservation debt (Azar and Holmberg, 1995). As long as we stay in this indebted zone, there seems to be no SOS. We then have to develop shadow pricing in a way consistent with the target, for instance, planetary boundaries and ecological footprints equivalent to one Earth's capacity.

A particularly helpful input might lie in the ongoing debate on the social cost of carbon (SCC) and the target-consistent approach. In a recent critique, Stern and Stiglitz (2022) argue that, given sheer uncertainty and sensitivity in the underlying integrated assessment model (IAM) and damage function, as well as unseen impacts of externalities and intergenerational equity, the SCC based on an IAM cannot be appropriate for our endeavor to push all economies to net-zero emissions. The authors propose we shift to the target-consistent approach that does not go deep into estimating SCC, although their targets need to be carefully determined in a way that is backed by scientific evidence, not by some political compromise (Aldy *et al.*, 2021a,b).

These perspectives sound familiar in the discussion of natural capital. In regard to global natural capital at least, a cost-effectiveness approach should be considered, as well as usual cost–benefit analysis, to rewind human impact. It has been argued that the same set of shadow prices as used in wealth accounting can be used for prospective policy evaluation (Collins *et al.*, 2017; Dasgupta, 2009). For example, a conservation program of natural capital can be evaluated by an ex ante cost–benefit analysis, using on the cost side the shadow rental prices of produced and human capital to be deployed in the program, with the shadow price of natural capital to be conserved on the benefit side.

It seems challenging, if not impossible, however, to quantify shadow values of some services that arise from natural capital, such as existence or spiritual services, or even some instrumental services. One way to circumvent this issue is to measure only what can be measured; the resulting shadow price of natural capital should be treated as a very low estimate. Alternatively, one can perform a break-even analysis, setting the benefit as an unknown. In another way, the planner might want to fall back on a cost-effectiveness analysis. Indeed, if a plausible target on the level of natural capital is already set, which the global community has agreed to achieve at whatever cost, as seen in the recent initiative to designate 30% of land as protected area by 2030, then the benefit of achieving the target becomes less relevant than the cost of doing so. The problem is now shifted to how to achieve the target in a cost-effective manner, comparing several alternatives and pathways. Shadow prices in the arena of the target-consistent cost-effectiveness approach might or might not coincide with those shadow prices in wealth accounting and cost-benefit analysis, which provides an area of future research.

5 Natural Capital Assets

5.1 Gray Natural Capital

Nonrenewable natural capital contains fossil fuel resources and mineral and metal resources. After all, they still account for half of the value of the change in the natural capital of nations (Figures 1 and 2) (World Bank, 2021). We could put them together and refer to them as gray natural capital, but for slightly different reasons. In the absence of postemission carbon capture instruments, fossil fuel use inherently

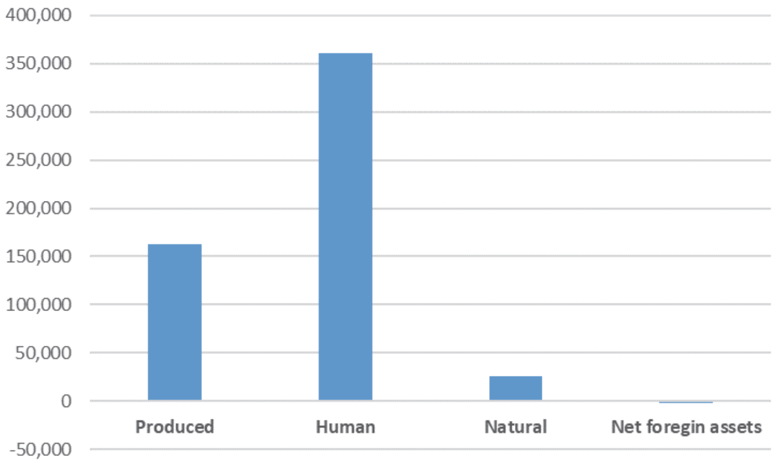

Figure 1: Composition of the value of the change in capital assets of nations, 1995–2018.

Note: The values are in constant 2018 US dollars at market exchange rates (World Bank, 2021).

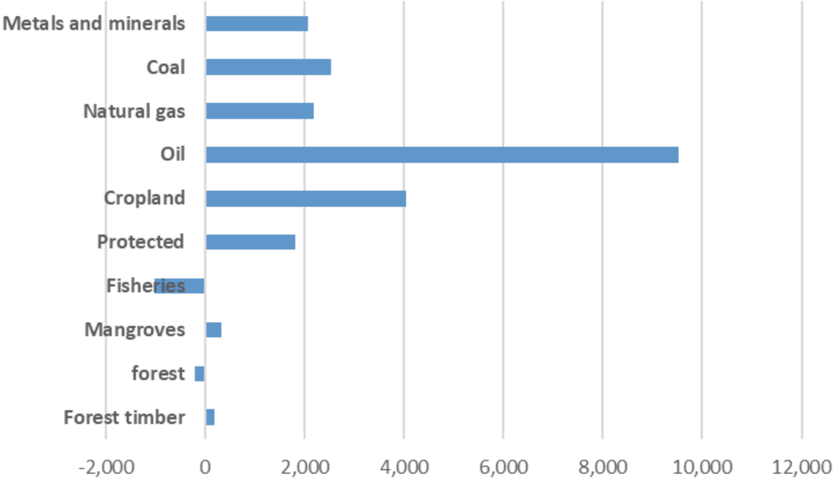

Figure 2: Composition of the value of the change in natural capital components, 1995–2018.

Note: The values are in constant 2018 US dollars at market exchange rates (World Bank, 2021).

damages climate stability as a form of global natural capital, whereas minerals and metals are associated with environmental externalities upon the production of their virgin products.

The valuation of gray natural capital can be either forward- or present-looking. A forward-looking shadow value is just the summation of future income flows expected from a unit of deposit:

$$p_S = \sum_{\tau=t}^{T} \frac{D_\tau}{(1+\rho)\tau} \tag{9}$$

where $\rho > 0$ is the social discount rate, $T > t$ is the terminal period and D is the resource rent (World Bank, 2021). $T - t$ is usually computed by the well-known reserve/production ratio, which is often a proxy for the remaining life years of the resource. The other present-looking methodology simply takes a snapshot of the whole deposit value by multiplying the stock quantity and its shadow rental price, typically its market price of some kind, net of marginal extraction cost. Note that this direct methodology to capture the whole stock does not give us the "stock value" by any means, in that the shadow price should always be measured at the margin. The "stock value" is of use only for the purpose of measuring the value of the change in capital assets across time (and accounting for the price change if any).

There is also a hybrid of the two, capturing the net present value (NPV) of future income flows divided by the total capital stock quantity to reach the average shadow price (Hamilton, 2016; Hamilton and Hepburn, 2017). These methodologies are still expected to give rise to widely different valuations (Atkinson and Hamilton, 2007).

We are also increasingly facing up to the reality that the transition to net-zero carbon economies requires massive input of mineral and metal resources for electrification. This could end up substituting the use of fossil fuels with the use of mineral resources within the gray natural capital class. Some even predict the rise of "electro states", much like oil-rich nations, which recalls the need to assess the sustainability of nations, including natural assets and sovereign wealth funds (Van der Ploeg, 2010) or at least net foreign assets (World Bank, 2021).

Unlike fossil fuels without carbon capture, the extraction of mineral resources might not necessarily translate into damage to society. However, extraction is still subject to environmental damage, as well as classic exhaustible resource constraints. In a model of mineral and backstop resources that are invested into capital formation, Pommeret *et al.* (2022) show that recycling could make the energy transition less costly. This implies that there might also arise a need to look into the material stock in use as "urban mines". as well as in ore in the lithosphere and in waste deposits, as they together represent the potential resource base that can be recycled and reused in circular economies. The now vast literature of material flow analysis and industrial ecology can be a useful inspiration (e.g., Gordon *et al.*, 2006).

5.2 Green Natural Capital

Green natural capital, by which we mean the renewable stock of natural resources, could take many forms. It has been a source of intensive research for the past decades, as it constitutes a source of a wide variety of biodiversity as well as ecosystem service flows, and we are literally embedded into this class of natural capital. National natural capital accounting, however, frequently uses area-based categories of agricultural land, forests, and protected lands in the terrestrial system. In principle, their shadow value can be prospectively captured by virtually the same equation as in gray natural capital, that is, the NPV of ecosystem service flow D that arises in the future:

$$p_S = \sum_{\tau=t}^{T} \frac{D_\tau}{(1+\rho)^\tau} \tag{10}$$

with ρ being the social discount rate.

The core of this exercise lies in expressing the income gain D from a unit of natural capital. Like gray natural capital again, they are some composite numbers of resource rents, that is, the net gain after harvesting costs in the case of forests and agricultural land. If natural capital has an amenity value, it can also be incorporated, but its connection to the underlying natural capital dynamics is rarely captured (Fenichel *et al.*, 2018). Conceptually Eq. (10) looks simple, but numerous theoretical and empirical challenges remain, such as the measurement of nonmarketed services, outside applicability, scalability, general vs. partial equilibrium considerations, and aggregation across space and time, among other issues. For example, if the shadow price attached to the same volume of income from natural capital differs, then there should be some laborious exercise behind the computation of D. Addicott and Fenichel (2019) examine spatial aggregation when the shadow price function might not be linear. Even if natural capital income is characterized by nonrivalry, people might exhibit different willingness to pay for a unit of natural capital due to heterogenous income distribution (Meya *et al.*, 2020).

Methodologically more challenging is the protected land category. Due to a lack of better data, World Bank (2021) uses the agricultural land shadow price for valuing protected land as well, so their valuation should be seen as a minimum estimate. In a move toward "30 by 30" to designate 30% of terrestrial land as protected land, we are tempted to expect that its quantity and value will account for more of nations' natural capital and wealth. However, that might not be the case, principally due to the problem of additionality compared with the baseline with no policy interventions (Pattanayak *et al.*, 2010). Moreover, if the forest is converted to agricultural land, the net gain of natural capital on the margin can be the difference between the shadow prices of forest and agricultural land, which could be negative (Hamilton and Atkinson, 2006). The same can be applied to the mere conversion of forests or (perhaps abandoned) agricultural land into protected areas. Even if the total area of land is fixed, the shadow price differential between pre- and postconversion could be positive if proper conservation takes place.

Another issue that concerns natural capital accounting is the denominator in the NPV formulas (9) and (10). Fenichel and Abbott (2014) derive the shadow price formula from the adjoint equation of natural capital, in which the marginal regeneration of (green) natural capital is deducted from the social discount rate. Furthermore, the social discount rate should capture the proper tradeoff between consumption and capital assets. If natural capital income is expected to be scarcer than consumption goods, then a relative price effect should also be factored in (Hoel and Sterner, 2007). Despite all this, most studies use the constant social discount rate of 4% or 5%. In their recent World Bank (2021) study, the growth rate of income from natural capital is also accounted for, which sometimes captures the impact of climate change and soil degradation on future crop yield growth rates. Although this appears in the numerator of NPV (D), this is equivalent to including regeneration in the denominator à la Fenichel and Abbott. Note also that the U.S. Office of Management and Budget (2003) recommended 7% and 3% for investment and consumption rates of return, respectively, which are used in the study of discontinuous action–inaction management of forests (Hashida and Fenichel, 2022). All of the above figures are higher than a recent expert survey on the social consumption discount rate for climate change analysis (Drupp *et al.*, 2018). The divergence is not necessarily implausible, however, given the different time horizon, numeraire, uncertainty, and objective of the study.

Finally, the current state of measuring D in the NPV has progressed, but there still remains a substantial, immeasurable portion that has yet to appear in practical accounting. For example, the invisible part of green natural capital is the land on which they sit: soil (Dominati *et al.*, 2010). This dark matter is a source of biodiversity aboveground (Dasgupta, 2021). Although they can be integrated into the annual income from aboveground natural capital (trees and agricultural land), soil could be worth a separate treatment, as it explains a portion of agricultural land productivity as captured by the normalized difference vegetation index (NDVI) and, moreover, persistent poverty (Barbier and di Falco, 2021).

Along with recreational, spiritual, and existence values (Bastien-Olvera and Moore, 2021), the contribution of natural capital to mental health has become increasingly noticed (Brandon *et al.*, 2021; Bratman *et al.*, 2019).[5] Amidst the global pandemic that crams people indoors, this value is “monetized”, as in the case of park prescription programs in North America.

5.3 Blue Natural Capital

Since the times of Adam Smith and David Ricardo, natural capital valuation has been centered on terrestrial natural capital. Although the oceans and marine worlds still account for a tiny portion of national wealth, it is a largely unexplored area of natural capital research. UNU-IHDP and UNEP (2012, 2014), Managi and Kumar (2018), and UNEP (2022) are earlier attempts to incorporate fisheries into national wealth

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[5] Other papers in the recent symposium issue of *Review of Environmental Economics and Policy* include more and subtler issues of green natural capital valuation (Polasky and Daily, 2021).

accounting.[6] Using panel data from 1951 to 2010 for 70 countries, Sugiawan *et al.* (2017) estimate marine fish stock by a production function approach and find that the economic growth initially leads to the deterioration of the marine ecosystem. Yun *et al.* (2017) study fish stocks that provide both provisioning services (harvest) and prey services to other valued predator fish. Once the shadow price is computed correctly, the prey service should not be accounted for. Kvamsdal *et al.* (2020) present a model of a three-species ocean ecosystem applied to the Barents Sea.

Fisheries do constitute an important class, but they are not the whole story of blue natural capital. Marine natural capital spans from produced capital (ports, oil rigs, other gray natural capital facilities, and ships and fishing gear) to natural capital (fisheries, whales as recreational capital, coastal mangroves, and the ocean as a climate regulator), if not human capital. These assets might yield income flows and products, much like economies on land. Fenichel *et al.* (2020) summarize value added, income, and assets in a dashboard that helps us keep track of both flows and stocks from a socioeconomic perspective. Blue natural capital is particularly relevant in the context of the tourism industry and small-island nations, which have been severely hit by the latest pandemic (White and Rahill, 2021). In addition, we should not forget that the ocean constitutes a large sink of carbon dioxide. Bertram *et al.* (2021) concentrate on the capacity of coastal blue natural capital to store carbon, which they believe contributes to US\$190.67 ± 30 bn per annum, based on the frequently used SCC valuation.[7]

5.4 Wild Natural Capital

To date, the natural capital discussion has largely ignored mobile natural capital. This is reflected in the three characteristics of natural capital depicted in Dasgupta (2021): invisibility, silence, and mobility. Mobility makes it difficult to attach property rights to the object, which makes natural capital and wealth accounting tend to be an area-based,

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[6] A persistent practical issue here is again related to mobility, where national attribution of fishery wealth might need more justification than just proportionality to harvesting.

[7] In finalizing the series of natural capital with colors here, we are tempted to produce the promising class of black natural capital that extends to outer space, but it is still early days.

instead of population-based, exercise. Flora and fauna, despite their symbolic and ecosystem significance, do not appear per se in natural capital accounting, although they might have been partially captured in estimating the ecosystem service flow from forest and agricultural land (e.g., through pollinators) in Eq. (10).

The recent global pandemic has reminded us of the cost of pushing the border of the animal kingdom and making them more marginalized.[8] Looking elsewhere, there is a pile of studies that examine the economics of wildlife, typically from the perspective of illegal trade ('t Sas-Rolfes *et al.*, 2019). Thomas-Walters *et al.* (2022) point to the need to incorporate qualitative research to study socioeconomic drivers of the conservation of threatened species. These findings and shared data can be fed back into the valuation of natural capital, possibly in a coupled human and natural system framework. In a recent study of the predator–prey ecosystem as natural capital affected by produced capital, Maher *et al.* (2020) show shadow price dynamics of inescapably declining populations of caribou from interactions with wolves, using preferences revealed in current conservation policies. The authors also estimate the conservation debt as the dent in the value of depreciation of natural capital traceable to human activities.

5.5 Renewable Energy Capital

Last but not least, a peculiar form of natural capital has increased its relevance in the would-be decarbonized society: REC. In view of the production boundary, REC is not a natural capital asset but a produced capital asset, as it is obviously not given by nature but manufactured by humans. However, once we note that the service flow that arises from REC is a joint product from renewable inputs directly given by nature (i.e., wind, solar, and other sources of energy) and REC, the REC service flow can be capitalized into a single value (with the use of an appropriate discount rate), in much the same way as

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[8] The pandemic has also yielded a flood of papers on the epidemiological susceptible–infected–recovered (SIR) dynamics incorporated into the macroeconomy (Acemoglu *et al.*, 2021). In principle, this can also be combined with other capital assets in the wealth accounting framework. Mavi *et al.* (2022) modify labor input by the infected–susceptible ratio and derive Hartwick's rule under pandemic uncertainty. However, the time horizon of the SIR dynamics might be much shorter than that of other capital assets.

ecosystem service flow can be capitalized into the associated natural capital value. Taxonomy aside, this forward-looking shadow pricing is applied in Yamaguchi and Managi (2019), who demonstrate that in some countries, the value of REC (for solar and wind) already starts to overgrow that of natural capital. Considering the speed with which investment into REC accelerates, this trend is expected to continue, as the World Bank (2021) recently recognized the value of REC (for solar, wind, and hydroenergy) across nations.

On the other hand, several drawbacks of massive investment in REC have also been reported. They include aesthetic issues (Maddison *et al.*, 2022), social acceptance, dramatic consumption of (often rare) materials, expected disuse of end-of-life REC that has yet to come in several decades, and competing use of land. This latter issue is of particular concern, as REC might dominate land that has a potential value for agriculture, carbon sequestration, or the protection of biodiversity, depending on the type of ex ante land use.[9] Whether the unit shadow price of REC exceeds its opportunity cost is a context-dependent question. Consequently, a social cost–benefit analysis is needed á la Dasgupta (2009) and Collins *et al.* (2017), where REC accounting provides a useful piece of information. Moreover, given its wide consequences on material consumption, land use, and end-stage waste, life-cycle analysis has a clear role in the social cost–benefit analysis of REC.

More interesting is how REC will substitute for the produced capital of conventional energy (coal or oil-fired power plants) and nonrenewable natural capital (fossil fuels) (Yamaguchi and Managi, 2019). They likely have different impacts on welfare and sustainability change: assuming that the energy service flows are the same before and after an introduction of REC, REC's substitution of produced capital does not change wealth, but REC's substitution of nonrenewable natural capital *increases* wealth. The empirical research is yet to be seen but could be undertaken as there are tradable markets for REC, in line with the revealed preference study of complementarity versus substitution between produced and natural capital (Rouhi Rad *et al.*, 2021).

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[9] In the analysis of siting patterns, Kim *et al.* (2021) find that not only large-scale solar photovoltaics but also medium-scale solar photovoltaics lead to significant habitat loss.

As discussed in Section 4, the importance of comparison with counterfactuals cannot be overstated (OSTP *et al.*, 2022). If the marginal value of REC is smaller than counterfactuals, it would negatively affect intergenerational well-being. Of course, in some cases, the alternative use value could be negligible. Offshore wind power is a case in point, and there are many examples of solar farms constructed on abandoned land and photovoltaic panels retrofitted on house roofs. In other cases, however, the marginal value of REC could be smaller than that of the alternative use of the land, as we have already touched upon biodiversity loss and disamenity. Their consequences are addressed in the aggregate if the increase in REC and the associated loss in other capital assets are properly recorded in national accounting. However, they should also be captured in the context of prospective cost–benefit analysis.

6 Population

In regard to biodiversity and natural capital on a planetary scale, the human population matters. Although there has been a discussion on whether to assess sustainability based on total capital stocks or capital stocks per capita, it is clear that total capital stocks matter in terms of the human impact on global biodiversity. This sheer fact is often overlooked, but the *Dasgupta Review* reminded readers of it, which points to the negligence of the matter in both the Paris Agreement and the SDGs. In fact, the *Review* even has a dedicated chapter on population. The *Review* observes social externality in both fertility behavior and population externalities that aggravate impact inequality. Although the *Review* does not go further to propose that a Pigouvian tax be imposed on populations, it reminds us that gender empowerment programs might also contribute to lessening the pressure on natural capital.

Meanwhile, population pressure should also enter sustainability assessments in per capita terms. In the most pristine form, investment in wealth or genuine savings per capita should be considered if the population is changing (Arrow *et al.*, 2004). However, it has been pointed out that population size and composition can also be considered capital assets. In such a setting, Arrow *et al.* (2003) and Asheim (2004) show that the value of the change in wealth per capita is not necessarily an accurate indicator of improvement in well-being, as the additional population might not be able to make up for the dilution of capital when the population is increasing nonexponentially (Ferreira *et al.*, 2008). In addition, the demographic transition to aging societies can increase the cost of population change (Yamaguchi, 2014). A recent pair of papers dig deeper into this issue to establish wealth investment rules for sustainability. In a Dasgupta-Heal-Solow-Stiglitz economy of capital accumulation and natural capital depletion, Asheim *et al.* (2021) look at such a rule to sustain NNP per capita to find that the capital dilution effect of population growth should be included in produced capital but not in nonrenewable natural capital. Such asymmetry arises because of capital gains accrued on nonrenewable natural capital. Given a long-lasting debate on the inclusion of capital gains in welfare improvement and wealth measurement (Asheim, 1996; Cairns, 2018; Hamilton and Ruta, 2009; Van der Ploeg, 2010; Vincent *et al.*, 1997), this distinction matters.

Moreover, Asheim *et al.* (2022) study investment rules to keep per capita consumption stable when the population changes, extending the seminal contributions of Hartwick (1977) and Dixit *et al.* (1980). The basic insight is that nonnegative genuine savings per capita (sustainability in the sense of nondeclining well-being) might not be sufficient to sustain per capita consumption (sustainability in the sense of Solow (1974)). The authors show that if an increasing population coincides with a relatively large consumption–wage gap, this insufficiency might increase because in such an environment, the additional population would contribute more to consumption than to labor. Other things being equal, the divergence between genuine savings per capita and the savings required to maintain per capita consumption could be widened by lower discounting, which is a plausible assumption when considering sustainable per capita consumption. Interestingly, countries that might fall short of investment to maintain per capita consumption include both high-income countries and lower-income sub-Saharan countries where genuine savings have been known to be barely positive. High-income countries expecting more population growth might also need to invest more into various forms of capital to keep the current, already high per capita consumption level.

7 Concluding Remarks

We have seen recent developments in natural capital and inclusive or comprehensive wealth accounting. Aiming toward climate and biodiversity targets in economies constrained with carbon budgets and planetary boundaries, wealth accounting needs to be updated to reflect global scarcities. The *Dasgupta Review*'s focus, influenced from UNEP inclusive wealth report, on impact inequality and the SOS approach might give us some toolkits to do that. In accordance, spatial and global aggregation and upscaling of micro to macro is also welcomed. This also calls for utilizing the wealth index for cost-effectiveness, as well as cost–benefit analysis, in parallel with the discussion around the SCC.

Although the underlying idea is straightforward, there remains much to be done in terms of the extension and application of sustainability analysis. We have not touched upon risk and uncertainty, which eats into the core of future flow from natural capital. Previous studies have shown that generally more investment is needed than what is suggested by simple genuine savings in stochastic settings characterized by Ito processes (Agliardi, 2011; Mäler and Li, 2010). Some recent studies incorporate such processes into specific natural capital asset pricing (Abbott *et al.*, 2021; Gollier, 2019). Given the current discussion on deep uncertainty in climate change, expanding this line of research to encompass Knightian uncertainty and ambiguity would be promising in natural capital and wealth accounting (cf. Baumgärtner and Quaas, 2009; Millner *et al.*, 2013).

Along with SEEA as an extension of national accounting, wealth accounting has gained much more attention than comprehensive or green NNP over the past decades. However, as mentioned in Section 1, the change in real NNP also moves in the same direction as the change in social well-being, provided that NNP is measured using proper shadow prices, in particular, Divisia measures of real consumption prices. Given that the literature is relevant to the wider "beyond GDP" discussion, this means that the largely unexplored measurement of NNP constitutes a very fruitful area of empirical research. An exception in this line of empirical research is Mota *et al.* (2010), who compare genuine savings (i.e., the value of the change in wealth) and comprehensive or green NNP over a decade for sustainability implications. In a separate context, Asheim (2010) argues that real green NNP might be more suitable than wealth for a cross-sectional comparison of per capita welfare. This observation could be utilized in the recent exercise of welfare comparison across countries that incorporates inequality and leisure (Jones and Klenow, 2016).

We have not covered some technical improvements in natural capital accounting. This includes the use of machine learning for natural capital change attribution (Shah *et al.*, 2021), the use of remote sensing and satellite imaging for forest capital accounting (Lange *et al.*, 2018), and the use of artificial intelligence for ecosystem accounting (Balbi *et al.*, 2022).

Along with methodological updates, future challenges include interlinkages of capital assets that complicate shadow pricing. Pollution and health is an imminent example. According to Global Burden of Disease studies, a few million die annually around the world as a result of exposure to indoor and ambient air pollution. Nevertheless, this is not reflected in national wealth and well-being records, although it is possibly embodied in the valuation of human and health capital, which would have been larger without such pollution. There are some exceptions marking earlier attempts to account for pollution in the change in wealth (McGrath *et al.*, 2019; Pezzey, 2004). This linkage between pollution and human and health capital should be studied in-depth in the framework of wealth accounting to vividly show this serious (and addressable) threat to humanity. There is a long-standing literature on the welfare (or well-being) significance of ‘real national income’. The modern literature began with John Hicks, then, Paul Samuelson, and subsequently James Mirrlees, Amartya Sen and Partha Dasgupta. Each of these studied a ‘timeless economy’, where an economy of ‘relative prices’ in the economy are constant over time. It is a feature of the equivalence theorem that in defining wealth, the weights that are to be attached to capital assets (including natural capital) with accounting prices of inclusive wealth report (UNEP, 2022), not exchange prices. Future studies need to focus how theoretically driven empirics make a difference in the policy making.

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