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Global Ecological Footprint and the Sustainable Development Goals

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Abstract

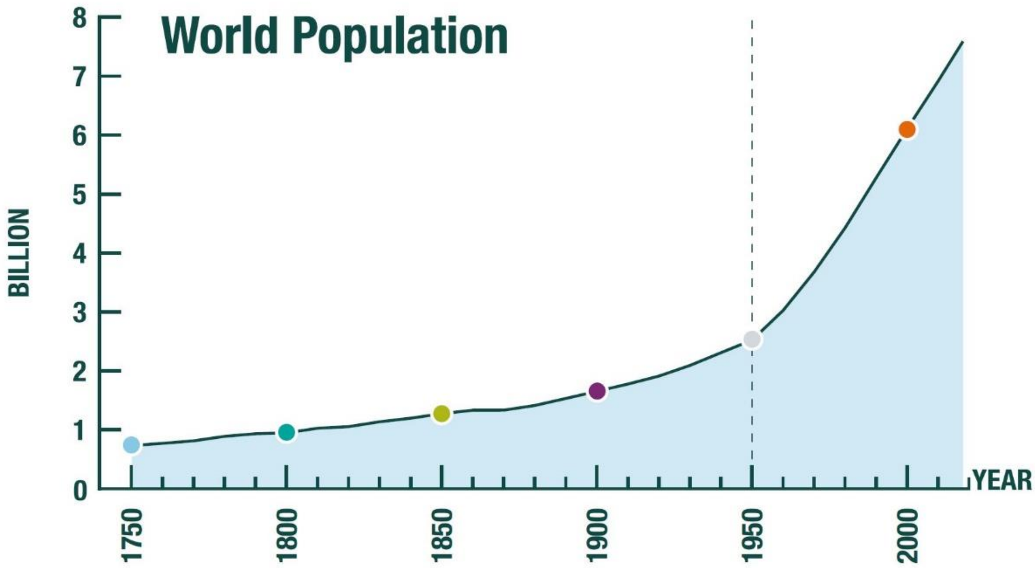
The Anthropocene can be read as being the era when the demand humanity makes on the biosphere's goods and services - humanity's 'ecological footprint' - vastly exceeds its ability to supply it on a sustainable basis. We call the gap between demand and sustainable supply the Impact Inequality. Because the gap is met by a diminution of the biosphere, the inequality is increasing. We adapt Ehrlich and Holdren (1971) to decompose humanity's ecological footprint into world population, per capita global GDP, and the efficiency with which the biosphere's goods and services are converted into global GDP. We then deploy estimates of the Impact Inequality, world output and its growth rates in recent years, and the rate at which the accounting value of natural capital has declined to study two questions: (i) At what rate must efficiency rise if the UN's Sustainable Development Goals for year 2030 are to be sustainable; (ii) What would a sustainable figure for world population be if per capita global GDP is to be maintained at an acceptably high level?

Key Words: biosphere, ecological footprint, sustainable development goals, impact inequality, natural regeneration rate

1 The Global Economy in the Anthropocene

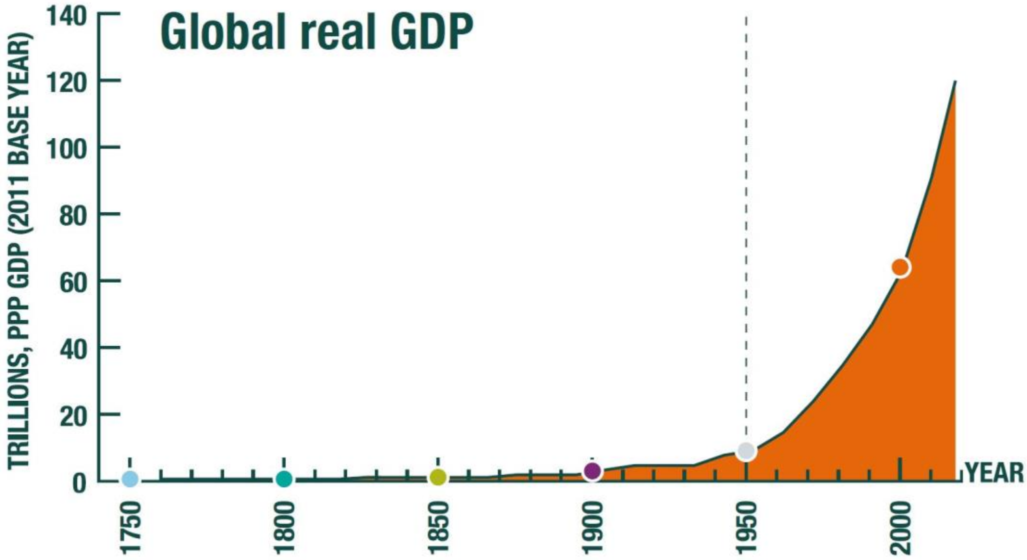
World population in 1950 was approximately 2.5 billion (Fig. 1) and world output of final goods and services (i.e., global GDP) at 2011 prices a bit over 8.2 trillion dollars at purchasing price parity, PPP – henceforth, 'dollars' - (Fig. 2). The average person's annual income was about 3,300 dollars (Fig. 3), a high figure by historical standards. Since then the world has prospered beyond recognition. Life expectancy at birth in 1950 was 46, today it is above 72. The proportion of the world's population living in absolute poverty (currently taken to be 1.90 dollars) has fallen from nearly 60% in 1950 to less than 10% today. In 2019 the global population had grown to over 7.7 billion (Fig. 1) even while global GDP per capita had risen to nearly 16,000 dollars (at 2011 prices; Fig. 3). World GDP was a bit above 120 trillion dollars (at 2011 prices), meaning that globally measured economic activity had increased more than 14-fold in only 70 years, something that had not remotely been experienced before (Fig. 2).

Figure 1: Global Population since 1750 CE.



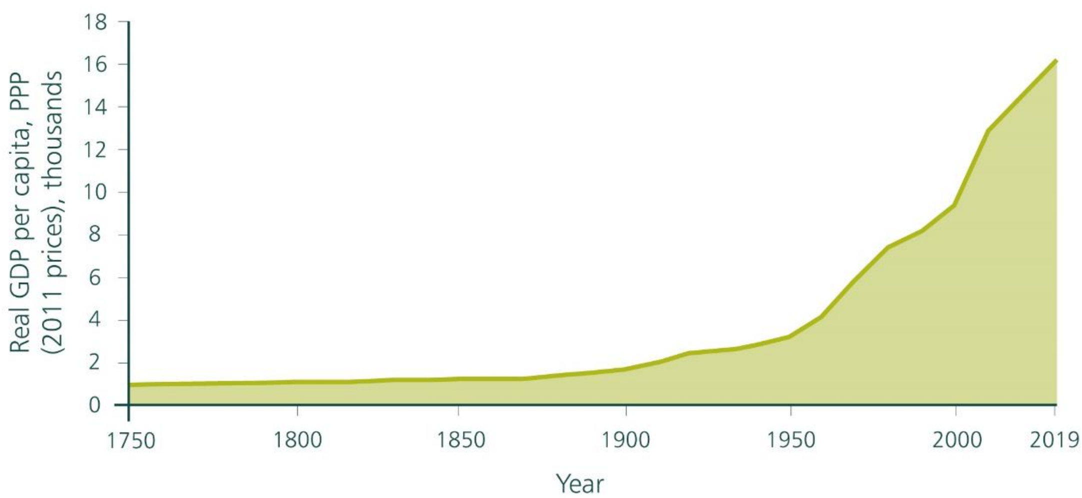
Source: UNPD (2019)

Figure 2: Global Real GDP since 1750 CE



Source: Our World in Data based on World Bank and Maddison (2017), Maddison Project Database, version 2018. J. Bolt, R. Inklaar, H. de Jong and J.L. van Zanden (2018), "Rebasing 'Maddison': new income comparisons and the shape of long-run economic development", Maddison Project Working paper 10.

Figure 3: Global Real GDP per Capita since 1750 CE



Source: Figures 1 & 2 (Dasgupta, 2021)

This extraordinary achievement has, however, come at a life threatening price, one which environmental scientists have been pointing to for some time. We are causing species extinction at 100-1,000 times the average extinction rate over the past several millions of years (the 'background rate') of 0.1-1 per million species per year, and the rate is continuing to rise. Allied to species extinction, the biosphere is being so degraded by human activities that a number of vital regulating and maintenance services (Section 2) we enjoy from it are increasingly threatened, the most prominent in the public eye being the stable climate in which our economies have evolved. The proposal by some Earth scientists (Voosen, 2016) that mid-20th century should be regarded as the time we entered a new era, the Anthropocene, matches Figures 1-3 exactly.[1]

2 Ecological Footprint and the Impact Inequality

The Anthropocene can be read as being the era when the demand humanity makes on the biosphere's goods and services in a period exceeds its ability to meet it on a sustainable basis. We call the gap between demand and supply the Impact Inquality.[2]

2.1 Global Demand

In a classic paper Ehrlich and Holdren (1971) called the demand humanity makes on Nature's goods and services in a period (e.g., a year) our *Impact* on the biosphere. Today it is common to call *Impact* our global *ecological footprint*. Humanity's footprint includes not only what we harvests from Nature, but also the services Nature offers for decomposing our waste (see below). Thus pollution is the reverse of conservation. For simplicity of notation we imagine the ecological footprint to be measurable quantity.

As *Impact* is caused by our activities, we need first to measurable as a scalar quantity.sure human activities and then convert them into ecological footprint. Global GDP is probably the closest we can get to measure human activities per period quantitatively, so we use that as our measure. However, it proves useful to decompose global GDP, as Ehrlich and Holdren did, into global population size and global GDP per capita (Ehrlich and Holdren called the latter, 'affluence'). Let N denote the former and y the latter. Global GDP is then Ny. Now let α be a numerical measure of the efficiency with which Nature's goods and services are converted by humanity into global GDP. Armed with these three factors that together make up the global ecological footprint, we may express global Impact as Ny/α. Each of the factors affects the other two (Section 3), and they in turn depend on both technology and institutions.[3]

2.2 Global Supply

The biosphere is a self-organising regenerative entity. So, set against the global ecological footprint is the biosphere's supply of goods and services. The Common International Classification of Ecosystem Services (CICES), which also identifies the contributions ecosystems make to human well-being, is built on the pioneering work of

[1] This paper applies the idea of sustainable development in the way it was formulated in what, to the best of our knowledge, was the last scientific publication of which our friend and mentor Karl-Göran Mäler was a signatory. We have tried to frame the questions posed here in a manner that, we hope, would have won his approval. We are grateful to Thomas Viegas for many helpful discussions on the material in Section 3.

[2] We use the terms Nature, the biosphere, the natural environment, and natural capital interchangeably.

[3] For example, our ability to harness energy from sources requiring smaller carbon emissions depends on our technological knowledge and the institutions we are able to create to put that knowledge to work. The aim would be to deploy technology and institutions so as to raise α.

the Millennium Ecosystem Assessment (MEA, 2005a-d). It consists of three categories of ecosystem services, contributing directly or indirectly to human well-being. They are:

1. *Provisioning Services* (*PS*). This category includes the provision of materials and energy needs for the range of products we obtain from ecosystems. It includes food, fresh water, fuel (dung, wood, twigs and leaves), fibre (grasses, timber, cotton, wool, silk), biochemicals and pharmaceuticals (medicines, food additives), genetic resources (genes and genetic information used for plant breeding and biotechnology), and ornamental resources (skins, shells, flowers).

2. *Regulating and Maintenance Services.* This category regulates and maintains ecosystem processes, including maintaining the gaseous composition of the atmosphere, regulating both local and global climate (temperature, precipitation, winds and currents), controlling erosion (retaining soil and preventing landslides), regulating the flow of water (the timing and magnitude of runoff, flooding, and aquifer recharge), purifying water and decomposing waste, regulating diseases (controlling the abundance of pathogens such as cholera and disease vectors such as mosquitoes), controlling crop/livestock pests and diseases, pollinating plants, and offering protection against storms (forests and woodlands on land, mangroves and coral reefs on coasts), recycling nutrients, and maintaining primary production and oxygen production through photosynthesis.

3. *Cultural Services*. This category offers non-material benefits, including spiritual experiences and an identification with religious values. It is perhaps more appropriate to trace these experiences and values to Nature, rather than ecosystems, since the latter is a term of recent origin. People find aesthetic value in Nature, which gives expression in private gardens and public parks and protected areas (forests and coast lines). Ecosystems influence social relationships (social capital in coastal fishing villages take a different form from social capital in nomadic herding and agricultural societies. The local ecosystem offers people a sense of place, their cultural landscape. And particular ecosystems attract tourism and recreation.

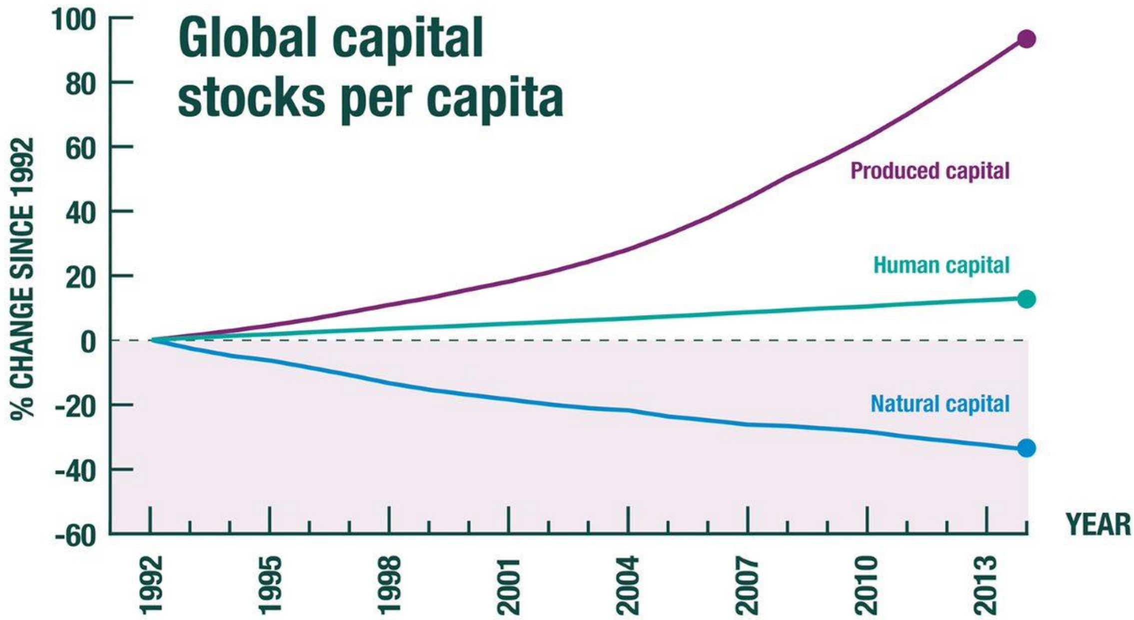
Provisioning, regulating/maintenance, and cultural services amount to a vector of goods and services per period. Here we suppose that it is possible to estimate their accounting prices and so arrive at a real aggregate measure, which we write as G, expressed in international dollars. G is a numerical measure of Nature's regenerative rate. Let S denote the biosphere as a stock. Then we may write $G = G(S)$. The biosphere is bounded. For simplicity, we simply extend the basic formulations of fisheries, soil, and forests, we suppose $\mathrm{d}G/\mathrm{d}S > 0$ for small S and $\mathrm{d}G/\mathrm{d}S < 0$ for large S.[4]

Humanity's ecological footprint does not have to equal G, because the difference would be accommodated by a change in the biosphere's stock, S. A world rich in healthy ecosystems could on Utilitarian grounds choose to draw down the biosphere (we call it *natural capital* here) somewhat and use the goods and services it supplies so as to accumulate *produced capital* (roads, buildings, machines) and *human capital* (education, health) by, say, felling timber to build homes and schools. That's what economic development has come to mean among many people. For example, in a major publication sponsored by the UN Environment Programme (Managi and Kumar, 2018), the authors have tracked produced capital, human capital and natural capital over the period 1992-2014 in 140 countries. Their estimates are that produced capital per head doubled and human capital per head increased by about 13%, but the value of the stock of natural capital per head (forests, fisheries, minerals) declined by nearly 40% (Fig. 4). Note

[4] We could introduce critical values of the biosphere easily into this framework, as in for example, $G(S) = rS[1 - S/K][(S - L)/K]$, where $L, r, K > 0$. Here L is the critical value.

though that the trend displayed in Fig. 4 cannot be maintained, because it involves depleting S. If the trend was to continue, G would collapse in due course, even as the biosphere tips over into a state in which human life could not exist.

Figure 4: Global Wealth per Capita, 1992-2014



Source: Managi and Kumar (2018)

2.3 Tradeoffs Between Ecological Services

It is significant that the processes governing regulating and maintenance services are either several steps removed from our direct experience or are felt by us only over the long run. Regulating and maintenance services are mostly hidden from view. They are also mostly silent. In contrast, provisioning and cultural services have readily detectable outcomes or are directly observable and can be felt even in the short run (e.g., in agricultural production, water deployment, forestry, fishing).

The competition humanity has created between the availability of provisioning services on the one hand and regulating and maintenance services on the other is vividly illustrated by tropical rainforests. These ecosystems produce goods such as fuelwood, fodder, timber, leaf manure, food, medicines, and supply such services as sequestering carbon, offering a habitat for wildlife and more generally housing biodiversity. Upstream forests also regulate waterflow (e.g., groundwater recharge, flood control) and conserve soil. The competing demands are a reason it is easy to overlook the significance of regulating and maintenance services; they are easy prey to economic development in the form the latter has been pursued. Over the years economic development has come to mean growth in the products we enjoy from provisioning services and such cultural services as tourism. But the pursuit of economic growth (i.e., growth in GDP) has led to a decline in the ability of the biosphere to supply regulating and maintenance services.

That decline endangers the biosphere's ability to supply provisioning, maintenance, and cultural services to our descendants.

2.4 The Impact Inequality

Ny/α is our proxy measure of the global ecological footprint. If the footprint exceeds the biosphere's regenerative rate G, the stock S diminishes. Similarly, if the footprint is less than the biosphere's regenerative rate, the stock increases. (Bifurcations leading to regime shifts and irreversibilities can be incorporated into this analysis, as in fn. 3.) However, either population or GDP per capita, or both, could increase without making additional demands on the biosphere provided α was to increase correspondingly. Improvements in technology (e.g., substituting degradable waste for persistent pollutants; decarbonizing the energy sector) and institutions and practices (e.g., establishing protected areas; reducing food waste), and appropriate redistributions of wealth are among the means by which α can be raised. Moreover, the G-function can be affected by policy. The application of bio-technology in agriculture is one avenue, another is ecosystem engineering.

But it is the defining feature of the Anthropocene that S has been declining as the gap between Ny/α and G has been increasing. We call the gap the Impact Inequality (Barrett et al., 2020; Dasgupta, 2021):

$$Ny/\alpha > G(S) \qquad (1)$$

In what follows we deploy the Impact Inequality for addressing two questions: (i) At what rate must α increase if the UN's Sustainable Development Goals (SDGs) for year 2030 are to be sustainable; (ii) What would a sustainable figure for global population N be if global GDP per head y is to be maintained at an acceptable high level? The questions are studied sequentially in the following two sections. Our estimates are based on very crude data. The calculations we offer are in effect back-of-the-envelope exercises, but that's because the applied economics of sustainable remains an underdeveloped field of enquiry.

3 The Sustainability of the UN's Sustainable Development Goals

In September 2015 the United Nations General Assembly agreed on an agenda for sustainable development in member countries. Nations committed themselves to meeting 17 Sustainable Development Goals by year 2030. The SDGs involve 169 socio-economic targets. To measure progress in meeting those targets, it was proposed to track more than 240 socio-economic indicators over the coming years.

International agreement on the SDGs was a remarkable, even noble, achievement, for the Goals unpick features of lives that would enable us to live well. But there is a problem. The Goals are not accompanied by an examination of whether, assuming they are achieved, they are sustainable. In view of the fact that we are now in a situation where there is an ever growing Impact Inequality, sustainability should as a bare minimum require that the inequality is converted into an equality.

So then, how large is the current overshoot of Ny/α over G? The Global Footprint Network defines ecological footprint not as Ny/α but as the ratio of Ny/α to $G(S)$. The Global Footprint Network (see Wackernagel and Beyers, 2019) have estimated that the ratio from 1 in about 1970 to 1.7 is 2019, implying that it increased at an average annual rate of 1.1%.[5] That means the ratio increased at an average annual rate of 1.1%.[6]

[5] In other words, in the late 1960s the global ecological footprint was sustainable but it is not today. The Global Footprint Network (GFN) picturesquely interprets the figure 1.7 as the number of Earths needed to match humanity's demands of the bisophere's goods and services on a sustainable basis. GFN has recently reported that the figure fell to 1.6 in 2020 due to the impacts of the COVID-19 pandemic.

[6] GFN's estimates are based on data furnished by the United Nations Statistical Office. For an account of the

Moreover, global GDP at constant prices has increased since 1970 at an average annual rate of 3.4%.

We turn to the right-hand side of the Impact Inequality. Managi and Kumar (2018) estimated that the value of per capita global natural capital declined by 40% between 1992 and 2014 (Fig.l 4). That converts to an annual percentage rate of decline of 2.3%. But world population grew approximately at 1.1% in that period. Taken together it follows that the value of global natural capital declined at an annual rate of 1.2%. Because there are no estimates of the form of the G-function, we assume for simplicity that local variation is a good approximation, meaning that G is proportional to S. So, G can also be taken to have declined at an annual rate of 1.2%.[7]

The estimates for the annual percentage rates of change of Ny, G, and $[Ny/\alpha]/G$ enable us to calculate that α had been increasing at an annual percentage rate of 3.5% in the period 1992 to 2014. Suppose we want to reach Impact Equality in year 2030. That would require $[Ny/\alpha]/G$ to shrink from its current value of 1.7 to 1 in 10 years' time, implying that it must decline at an average annual rate of 5.4%. Assuming global GDP continues to grow at 3.4% annually and G continues to decline at 1.2% (i.e. business is assumed to continue as usual), how fast must α rise?

To calculate that, let us write as g(X) the percentage rate of change of any variable X. We then have

$$\mathrm{g}([Ny/\alpha]/G) = \mathrm{g}(Ny) - \mathrm{g}(\alpha) - \mathrm{g}(G) \qquad (2)$$

Equation (2) can be re-arranged as

$$\mathrm{g}(\alpha) = \mathrm{g}(Ny) - \mathrm{g}([Ny/\alpha]/G) - \mathrm{g}(G) \qquad (3)$$

We now place the estimates of the terms on the right-hand side of equation (3) to obtain

$$\mathrm{g}(\alpha) = 0.034 + 0.054 + 0.012 = 0.1$$

In short, α must increase at an annual rate of 10%. As that is a huge hike from the historic rate of 3.5%, we consider a different scenario.

Suppose global GDP was to remain constant in real terms from now to year 2030 and draconian steps were taken by us over our demands to limit the rate of deterioration of the biosphere to an annual 0.1%. What would be required rate of increase in α need to be? Using equation (3) we have $\mathrm{g}(\alpha) = 0.054 + 0.001 = 5.5\%$. Even that is considerably larger than the 3.5% rate at which α has been increasing in recent decades.

4 How Many People Can Earth Support at an Acceptable Standard of Living?

Our decomposition of humanity's ecological footprint, Ny/α, could appear to show that substitution possibilities between N and y take the form of rectangular hyperbolae. Arithmetically that is true, but y would be expected to depend on N: we humans are not merely consumers, we are born with hands and a brain. Thus $y = y(N)$. In standard models of economic growth, $\mathrm{d}y/\mathrm{d}N < 0$, but the functional form is not that of a rectangular hyperbola.[8] We confirm that below in a simple model in a reduced form and

methods that are deployed for estimating G, see Wackernagel and Beyers (2019). It should be noted that as an approximation they take G to be linear in S.

[7] While Managi and Kumar (2018) base their work on the UN data base, the questions they ask differ from those asked by the GFN (Wackernagel and Beyers, 2019). Moreover, because the Managi-Kumar study includes fossil fuels and minerals, we must assume for our purposes of illustration that the percentage rate of global decline in the accounting value of sub-soil resources equalled the corresponding figure for ecological resources. Using data from different systems of measurement in the numerical calculation we conduct here is a price we have to pay for continual neglect of the economics of the biosphere in international organisations. GDP estimates have been refined continually over the decades by countless experts, whereas the human footprint on the biosphere remains of interest only to a handful of people.

[8] Dasgupta and Dasgupta (2017) posed the same question as we do here, but assumed that humans are mere consumers, that they are not producers of final gods and services.

ask how many people Earth can support at an acceptable living standard, given today's technology and capital structure. For the purposes of illustration we use the figure of 20,000 (international) dollars at today's prices. As the figure falls in the range of per capita incomes in the World Bank's list of upper middle-income countries, we use it to represent an acceptable standard of living.[9]

We assume that people apply their labour on produced capital (machines and equipment) and the biosphere's goods and services to produce an all-purpose commodity that can be consumed. As of now we have little quantitative knowledge of the biosphere's dynamics when viewed in the aggregate, that is, we don't know the *G*-function. But we know that expanding our stock of produced capital would very likely have environmental consequences. So, with both pairs of hands proverbially tied behind our backs we now regard K to be an aggregate measure of the biosphere and produced capital, which we then hold fixed.

Let Q be aggregate output. If global population is N and φ the proportion of N in production, we assume that

$$Q = K^{(1-\rho)}[\varphi N]^{\rho}, \qquad 0 \leq \rho < 1,\ 0 < \varphi < 1 \qquad (4)$$

We now stop K on its tracks and estimate $K^{(1-\rho)}$ (eq. (4)) on the basis of the current size of the world economy. Stopping K on its tracks amounts to imposing a quota on what the human population is permitted to take from the biosphere.

The latter thought is not outlandish. Quotas are applied routinely to fisheries and forestry, and for access to potable water in dry regions. The recent international agreement to limit the rise in mean global temperature to 1.5^{o}C above what it was in pre-industrial times is tantamount to the use of quotas in emissions. That said, we realize that applying the idea on the biosphere as whole is a leap of faith in the ability, not to mention willingness, of international organizations to reduce the ecological footprint to a sustainable size. But we have found no other way to estimate the size of the global population Earth can support at reasonable comfort. Wilson (2016) has made an impassioned plea to leave half of Earth free of human encroachment. Here we follow a somewhat different, and a lot more blunt, route to identify a sustainable socio-ecological state of affairs.

The data being utterly crude, we confine ourselves to pen-on-paper computations. We assume that the value of the world's production of final good and services draws proportionately on ecosystem services at all levels.[10] World output is currently about 120 trillion dollars. Using the model of production in equation (4), we therefore have

$$K^{1-\rho}[\varphi N]^{\rho} = 120 \text{ trillion dollars} \qquad (5)$$

World population is currently 7.8 billion. The global dependency ratio, that is, the ratio of the sum of the number of people below age 15 and above age 65 to the number of people between 15 and 65, is today about 1.6 to 1. Thus $\varphi = 1/2.6$, and so $\varphi N = 3$ billion. A huge empirical literature in economics suggests that as a rounded figure, $\rho = 0.5$ is not unreasonable. Equation (5) then says

$$K^{0.5} = 120\text{x}10^{12}/(3\text{x}10^{9})^{0.5} \text{ dollars per producer}^{0.5}$$
$$\approx 2.2 \text{ billion dollars per producer}^{0.5} \qquad (6)$$

Having calibrated our model of global production, we compute the sustainable population size at y = 20,000 dollars. Let N^* denote the size of the sustainable global population. To err on the conservative side of GFN's most recent estimate of 1.6, we

[9] We are not conducting an optimisation exercise, for that would require additional features in the model, such as a social objective function. On this see Dasgupta (2019).

[10] This would be an incorrect assumption in non-stationary states, because it ignores differences among sectors in the value that labour adds to production of output.

assume the global ecological footprint is currently 1.5. That means if the biosphere and the stock of produced capital were stopped on their tracks, their sustainable value would be $K/1.5$, which we denote by K^*. Using equation (6),

$$(K^*)^{0.5} \approx 1.8 \text{ billion dollars per producer}^{0.5} \quad (7)$$

Using equations (5)-(7), we have

$$(K^*)^{0.5}(\varphi N^*)^{0.5} = (1.8\text{x}10^9)\ (\varphi N^*)^{0.5} = (20\text{x}10^3)N^* \quad (8)$$

But $\varphi = 1/2.6$. From equation (8) it follows that

$$N^* = 3.32 \text{ billion} \quad (9)$$

Global population was about 3 billion in 1960 (Fig. 3); so, in 3.32 billion we are not staring at a figure from less than 60 years ago.

The estimate is revealing. Global population today is 7.8 billion and per capita consumption is 16,000 international dollars. Our estimate, with all the caveats we have stressed, says that if humanity were to find ways to husband the biosphere in a sustainable manner and to bring about economic equality, the population Earth could support at a living standard of 20,000 dollars is approximately 3.3 billion. It is a simple matter to conduct the exercise with alternative figures. We resist doing that.

5 Concluding Remarks

The Anthropocene can be read as being the era when humanity's ecological footprint vastly exceeds Earth's ability to supply our demands it on a sustainable basis. Because the gap (the Impact Inequality) is met by a diminution of the biosphere, the difference between humanity' demand and Nature's ability to meet that demand on a sustainable basis is increasing. In this paper, we have followed Barrett et al. (2020) in decomposing humanity's ecological footprint into world population, per capita global GDP, and the efficiency with which the biosphere's goods and services are converted into global GDP. We have deployed estimates of the Impact Inequality, world output and its growth rates in recent years, and the rate at which the accounting value of natural capital has declined to study two questions: (i) At what rate must efficiency rise if the UN's Sustainable Development Goals for year 2030 are to be sustainable; (ii) What would a sustainable figure for world population be if per capita global GDP is to be maintained at an acceptably high level?

In exploring question (ii) we have chosen 20,000 (international) dollars as the basis of the exercise. Our decision to study how many people Earth can support at that living standard in a *stationary state* was forced on us because of lack of data. We know that the biosphere can be thought to be a gigantic renewable natural resource, but we know next to nothing about the parameters that define its dynamics. So we have taken the desperate steps of freezing the biosphere and all other capital assets on their tracks and of calibrating the model by using estimates of our global ecological footprint. The idea that society can lock so complex an object as the Earth system on its tracks is not to be believed, but it's the only move we have had available to us for finding a way through a maze. The population figure we have reached on the basis of the calibration is not attainable in the near future, but we have presented it only to show how far off humanity is from where we should probably now be. Moreover, the estimate we have reached, of a bit over 3 billion people, was global population only some 60 years ago.

That human activity since the end of the Second World War has grown faster than ever before is now well appreciated. But formal economic models haven't studied its impact on the biosphere. Our aim has been to explore a mode of analysis for doing that, nothing more.[11]

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11 Cohen (1995) reviewed studies that had estimated Earth's human carrying capacity. The range he

reported was very wide (estimates, in billions, differed by nearly two orders of magnitude); but he didn't have at his disposal the ominous biogeochemical signatures that have been uncovered in recent years, nor the findings in MEA (2005a-d). Dasgupta (2021, Ch. 4*) presents a complete capital model that can be used to study both questions (i) and (ii) of this paper in a dynamic setting.

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