Ecological Footprint Accounting: Limitations and Criticism

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Introduction

Complementary Criticism is vital

The emergence of the Ecological Footprint in 1991 was inspired by a simple question: "How much do people take compared to what the Earth can renew?" While the question has not changed, the methodology has evolved to make answers sharper and more robust.

Over the last decades, Ecological Footprint results have been increasingly used. For instance, the annual Earth Overshoot Day campaign, which draws on those results, gets large-scale media exposure. In 2019, 6,500 trackable web-based stories generated over 4 billion media impressions in 120 countries.[2] 11,800 web-based stories were generated over the entire year. Additionally, for the last decade, about 250 academic papers on the Footprint have been published every year.[3]

Wide media exposure and striking results kindles responses, including critical voices. Ecological Footprint accounting is no exception. There is plenty of room for improvement in these accounts, therefore criticism is healthy and welcome. In fact, criticism is one of the key mechanisms of scientific progress.

Based on simple principles

Ecological Footprint and biocapacity accounting apply a basic scientific principle: By adding up all the human demands that compete for biologically productive space, you get the total space needed by human demands. Also there is no double-counting, meaning the same area is only counted once.[4] Thus, such accounts describe actual occurrences rather speculation.

Ecological Footprint and biocapacity are based on fundamentals. They do not require fancy math or science – no quantum physics, gravitational waves, or relativity theory. Resource accounting is based on rudimentary thermodynamics and the principle of conservation of mass. It is an accounting framework that allows anybody to track flows of matter and energy in a consistent, coherent way.

Still, applying these basic principles to households, companies, cities or countries can get complex. The accounts attempt to count all their demands competing for productive areas which requires large data inputs. Such comprehensive assessments can become convoluted and

[2] This is based on media search via the meltwater.com service.

[3] This is based on a "scopus" research scanning 2010-2019, searching for "ecological footprint" in either abstract, keywords, or title. In May 2020, Scholar.goole.com found 95'000 documents containing "ecological footprint". When searching for "environment"&"footprint" it found over 1.2 million entries.

[4] An introduction to basic principles behind Ecological Footprint accounting is provided in section 1 and 2 of the open access paper "Defying the Footprint Oracle: Implications of Country Resource Trends" available here.

complicated. For this very reason, Footprint standards were developed (they are available at www.footprintstandards.org).

Potential for improvement

Since Ecological Footprint accounting covers all human demands (which span over vast arrays of activities), data availability is one of the most limiting factors for the analysis. As a result of this, the options are relying on weak data, leaving things out, or making assumptions, all of which limit the robustness of the results.

The most prominent Ecological Footprint accounts are those for country-level assessments: the National Footprint and Biocapacity Accounts.[5] These particular accounts are based on all relevant UN statistics that are available. The accounts intentionally use UN (and para-UN) data to assure neutrality, comparability across countries, and compatibility with international standards. Prioritizing official sources and proof of concept allows us to focus on the robustness of the accounting framework while being aligned with ever evolving and improving international statistics. More accurate and complete assessments may exist in some cases and the framework is set up in such a way that allows new data to be integrated through the accounting workbook. Also, the option exists for any researcher to enhance the core resources of National Footprint and Biocapacity Accounts with further analysis based on additional non-UN data, as also explained in the Ecological Footprint standards (www.footprintstandards.org).

Recent editions of the National Footprint and Biocapacity Accounts use up to 15,000 data points per country and year. For many reasons there are, as they say, "devils in the detail". The majority of countries, especially those with long established statistics agencies, have complete and robust input data. However there are also many countries for which the data is not complete, categories do not match, or key aspects are not documented, etc. Given these information gaps, the execution does naturally not fully live up to the intended simplicity and clarity of the ideal underlying principles.

Applying the Ecological Footprint is an evolving discipline that benefits from criticism and fresh perspectives. All sincere criticism is beneficial, whether based on misunderstandings and confusion,[6] or on new insights and logical arguments. The former help to sharpen ways in which the principles behind the Ecological Footprint accounts and the results they produce are communicated. The latter enables the researchers to sharpen the method and find more effective ways to apply the tool.

[5] A description of the accounts, and recent improvements, is "Ecological Footprint Accounting for Countries: Updates and Results of the National Footprint Accounts, 2012–2018" available here.
[6] See for example a brief discussion on Greenbiz entitled "Ecological footprint accounting and its critics" available here.

What we have learned from criticism

Criticism has been vital to the development of the Ecological Footprint concept, and particularly one of its most prominent applications, the National Footprint and Biocapacity Accounts. Since the first national calculation in the early 1990s for Canada,[7] many things have changed and much of it because of feedback and criticisms.

Let us highlight some examples:

Criticism pointed out that hectares are a poor proxy for biological productivity, because some are highly productive (tropical rainforest, wetlands) while others much less so (tundra, steppe). This led us to introduce **global hectares**. Global hectares reflect the biological productivity of surface areas. This productivity varies from one hectare to the next, as well as over time, given changing climate and shifting agricultural practices.

Introducing global hectares also lead to deeper inquiries: we investigated how global hectares contrast and compare with Net Primary Productivity. Through that, we identified their respective benefits and limitations.[8]

In the early National Footprint and Biocapacity Accounts, we made an arbitrary choice to include **nuclear** electricity as if it was produced by coal. The rationale was that we did not want to take sides, or have the Footprint be misused as an argument for or against nuclear energy. We feared being caught in the middle will detract from the message of overshoot. We were rightly criticized for our initial approach. It was scientifically flawed as it did not reflect the

[7] Published in the PhD thesis of Mathis Wackernagel, "Ecological Footprint and Appropriated Carrying Capacity: A Tool for Planning Toward Sustainability." 1994. School of Community and Regional Planning. The University of British Columbia. https://dx.doi.org/10.14288/1.0088048

[8] Helmut Haberl initiated this inquiry through a special issue in Land Policy. Some of the relevant papers from this issue are:

- Haberl, H., Wackernagel, M., and Wrbka, T. 2004. "Editorial: Land use and sustainability indicators. An introduction" Land Use Policy 21 (2004) 193–198.
- Haberl, H., Wackernagel, M., Krausmann, F., Erb, K.-H., Monfreda, C., 2004. "Ecological Footprints and Human Appropriation of Net Primary Production: A Comparison." Land Use Policy, 21 (2004) 279–288.
- Krausmann, F., Haberl, H., Erb, K.-H., Wackernagel, M, 2004. "Resource flows and land use in Austria 1950-2000: Using the MEFA framework to monitor society-nature interaction for sustainability." Land Use Policy, 21 (2004) 215–230.
- Monfreda, C., Wackernagel, M., Deumling, D., 2004. "Establishing national natural capital accounts based on detailed ecological footprint and biological capacity accounts." Land Use Policy, 21 (2004) 231–246.
- Wackernagel, M., Monfreda, C, Erb, K.-H., Haberl, H., Schulz, N.B. 2004. "Ecological Footprint time series of Austria, the Philippines, and South Korea for 1961-1999: Comparing the conventional approach to an actual area demand approach." Land Use Policy, 21 (2004) 261–269.
- Wackernagel, M., Monfreda, C., Schulz, N.B., Erb, K.-H., Haberl, H., Krausmann, F. 2004. "Calculating national and global ecological footprint time series: Resolving conceptual challenges." Land Use Policy, 21 (2004) 271–278.

research question. Starting with the 2008 edition, the national Footprints only count nuclear for its direct biocapacity demands, mainly carbon emissions for building nuclear plants and procuring, managing, and disposing the fuel. Due to a lack of data, the biocapacity side does not included the loss in human access to biocapacity due to exclusion zones from accidents, particularly those of Chernobyl and Fukushima. It is important to note that such loss in biocapacity can, over time, be quite substantive.

In parallel, we emphasized that the Ecological Footprint methodology is not the most relevant framework for assessing the risks and benefits of nuclear energy. More significant are questions of costs, operational risks, long-term waste storage, and the potential for nuclear proliferation.[9]

For many more examples of how criticism has helped improve Ecological Footprint accounting see Section 5.

What this briefing document covers

If you have further questions or comments, please do not hesitate to send them to Global Footprint Network at info@footprintnetwork.org and include CRITICISM in the subject heading.

[9] For more discussion on the nuclear dimension, consult: - Wackernagel, M., A. Galli, L. Hanscom, D. Lin, L. Mailhes, T. Drummond (2018), CHAPTER 33: Ecological Footprint Accounts: Criticisms and Applications" p521-539 in Simon Bell and Stephen Morse (Editors) 2018. Routledge Handbook of Sustainability Indictors, Routledge International Handbooks. Routledge, https://www.routledgehandbooks.com; a draft is here.

SECTION 1: Should Footprint Accounts be trusted?

Don't trust. Test and verify.

Ask yourself: Are these accounts addressing a critical question for sustainability? Are they answering it better than any other metric? If so, will they increase your ability to make sounder bets about how to invest for a successful future?

Test any quantitative assessment, including Ecological Footprint accounting, with at least four fundamental, sequential questions:

1. Does the assessment build on a clearly defined, testable research question?
2. If yes, is the research question relevant to the intended audiences?
3. If yes, are more accurate methods available elsewhere for answering this particular research question?
4. If not, is society better off without the results this method generates (for instance because the results are too misleading)?

By following these logical steps, it becomes clear whether the results are helpful, or not.

These questions help to discern fundamentally different types of criticism:

- About the underlying principles (whether biocapacity is a useful lens to look at the material dependency of people on the planet's ecosystems)
- About how the underlying principles are translated into a measurement method (for instance the method behind the National Footprint and Biocapacity Accounts)
- About how well the method is executed (something that is also limited by data availability).

Ecological Footprint accounting builds on a simple research question: *How much of the biosphere's (or any region's) regenerative capacity does any human activity demand?* Or, more specifically: how much of the planet's (or a region's) regenerative capacity (or biocapacity) does a defined activity require from nature? This question is at the core of Ecological Footprint accounting (Wackernagel et al. 2018a,b; Wackernagel et al. 2019). Since regeneration is being outpaced by human demand, it seems that this question is deeply relevant to humanity's sustainability transformation.

We can even become more specific, defining regenerative capacity as the current (or in the case of built-up areas compromised) "potential net primary productivity." How much of a particular area is needed to provide for a particular demand, and how productive is this particular area compared to world average, where the relative productivity is determined by the relative "potential net primary productivity." This would be the ideal way. But since there is

no reliable global data set on potential net primary productivity, current assessments still build on GAEZ: the Global Agro-Ecological Zones.

The most systematic accounts at the country level are the National Footprint and Biocapacity Accounts, based on UN statistics. This accounting system is documented extensively elsewhere (Lin et al 2018, Borucke et al. 2013, Wackernagel et al., 1999, 2002). A brief introduction is included below. Papers, handbooks and descriptions are listed in the reference section. Key papers are also available here: www.footprintnetwork.org/resources/data.

Ecological Footprint accounts have been tested by over 10 national governments. And some national government agencies even reproduced them in their entirety, regenerating the time series. All of those reproductions were successful: www.footprintnetwork.org/reviews. The results of the National Footprint and Biocapacity Accounts are publicly available at http://data.footprintnetwork.org. The latest annual edition was released in 2019 – with data points up to 2016 (currently the latest year with a complete UN data set).

Yes, there are also published criticisms of Ecological Footprint accounting, and Global Footprint Network studies them carefully. Indeed, some have helped to improve the methodology or the communication. Here is a short discussion about such criticisms: https://www.greenbiz.com/article/ecological-footprint-accounting-and-its-critics and a more detailed discussion is in Wackernagel et al. (2018b).

SECTION 2: Why Ecological Footprint accounts are needed

Our argument is simple: there is no other possible future for each country, and humanity, than to eventually live off the planet's regeneration, not its liquidation. The only agency we have in the matter is to decide **how fast we will transition**. The earlier humanity transforms, the more resources will be left and easier it can fit within the planet's resource budget. Possibly even more important: early adopters will be far better positioned to succeed, as they will have their infrastructure (roads, cities, and power plants) adjusted in time. Embracing this transformation is ultimately a question of **competitiveness**.

We believe that emphasizing the significance of **resource security**, in particular of biological resources, could be beneficial for making the necessity of the transition more obvious. Our metric is the only comprehensive accounting system in the world that compares all competing demand on the biosphere (including carbon emissions) to what the planet can renew. It serves as the most **fundamental resource balance**: the size of the human economy compared to what the planet can provide.

While recognizing that metrics are not necessarily the motivator, and certainly not the only ingredient needed for transformation, it is hard to imagine a transition without clear metrics. They show where we are, how fast we are moving, and where we need to get.

To serve this need and boost ecological literacy, Global Footprint Network has provided, and continuously improved, the most comprehensive and robust accounts that compare people's material demand to Earth's regeneration.

Without a one-planet metric, there can be no meaningful management, no accountability, no evaluation of progress towards living within the means of our planet. It is the ultimate science-based target. Such a metric is fundamental to understanding our current state, including trends for humanity, countries or any sub-population. It can also help set goals, and monitor overall progress.

Our data, made available to countries, cities, companies, and citizens, provides reliable information about the ecological dependencies and risk exposure of countries, cities, and companies and supports them in managing their transition to sustainability.

SECTION 3: Ecological Footprint accounts - a short introduction to the underlying accounting principles

Ecological Footprint accounts have two sides: a) the availability of biocapacity and b) the human demand on biocapacity, called the Ecological Footprint. The Ecological Footprint represents all the mutually exclusive[10], biologically productive spaces that human activity demands. The Ecological Footprint of a person represents all the physical demands of that person associated with their consumption, including demands for food, fibre,[11] timber, space occupied for built infrastructure, and the space required to assimilate waste. Currently, the most significant waste of humanity is its CO_2 emissions as a result of burning fossil fuels.[12]

Adding up all the mutually excluding areas needed to provide for these demands becomes a simple accounting procedure. This accounting procedure makes it possible to measure the human demand on nature (Ecological Footprint) and contrast it with biocapacity. Demand on regeneration (the Ecological Footprint) as well as regenerative capacity (or biocapacity) are both expressed in biologically productive areas needed for this regeneration. To make areas comparable across the world, across various land-use types, and across time, they are expressed in "**global hectares**", which are biologically productive hectares with world average productivity in a given year.

In essence, Ecological Footprint and biocapacity accounts are based on simple, straightforward accounting principles ("add up competing demands for biocapacity"). Additionally, the accounts for countries are calculated exclusively with official data from the UN to avoid doubts about the input data.

With a clear focus also comes clear limitations. For some applications, overarching accounts like the Footprint may be too high-level. The accounts are not particularly helpful, and hence not meant to be used, for highly specific actions (e.g., "analysing water use of households"), or more detailed aspects (e.g., "the impact of an activity on microbes in the soil"). They are helpful to put various demands in context to each other. It helps to overcome a siloed perspective on environmental stresses. They rather provide context. Such context may be useful for more

[10] Mutually exclusive means that only those uses that exclude other uses are counted. Otherwise there is double counting. For example, if potatoes are grown on a field, the same space cannot occupy a forest at the same time. The two uses mutually exclude each other.

[11] For instance, for clothes, paper, or building materials.

[12] See data.footprintnetwork.org or Lin, David; Hanscom, Laurel; Murthy, Adeline; Galli, Alessandro; Evans, Mikel; Neill, Evan; Mancini, Maria S.; Martindill, Jon; Medouar, Fatime-Zahra; Huang, Shiyu; Wackernagel, Mathis. 2018. "Ecological Footprint Accounting for Countries: Updates and Results of the National Footprint Accounts, 2012–2018." Resources 7, no. 3: 58. https://www.mdpi.com/2079-9276/7/3/58

detailed, more specialized tools examining the specifics of one domain, like soil health, water usage, plastic waste etc. If we seriously recognize the need to address climate, the challenge is not just to eliminate carbon emissions, but also to increase sequestration and to find ways to operate our entire economies within planetary regeneration. That, and solar income on biologically non-productive areas, are the only significant physical budgets available from nature post the fossil fuel age.[13]

This section provides some key results for context, and then addresses three conceptual issues:

3a) Ecological Footprint accounts – some basic numbers

Earth's surface stretches over 51 billion hectares.[14] According to FAO, of these hectares, 12.2 billion harbour the majority of the biological productivity area, including continental shelves of oceans, forests, and cropland. Given that global hectares represent world average productive hectares, these 12.2 billion hectares are also worth 12.2 billion **global hectares**. In other words, each global hectare represents about a 12.2 billionth of the planet's regeneration.

Footprint accounting is possible at any scale, from humanity's total demand on nature down to the demand of a country, city, individual or a single activity. Details on Ecological Footprint and biocapacity accounting can be found in the reference section of this document under "More on the Ecological Footprint".

Global Footprint Network has maintained national calculations since the organization's inception in 2003 by building on earlier ones starting in 1997. The annually updated calculations are called National Footprint and Biocapacity Accounts and are entirely based on UN data sets. All results are available on an open data platform (data.footprintnetwork.org). The latest edition of these accounts, published in 2019, shows

[13] Yes, there are also some other minor energy budgets, including lunar energy by harnessing tidal flows, fusion and fission.

[14] In the aftermath of the French Revolution, the French defined the kilometer as a 10 000th of the distance from the Equator to the North pole, or a 40 000th part of the length of the circumference of the planet. The initial measure in 1799, was about 0.02% off. Still assuming a circumference of 40 000 km which would lead to a spherical surface of $4 * \pi * r^2 = 50.9$ billion hectares.

that in 2016, the most recent year for which UN data sets are complete, humanity's demand exceeded the planet's biocapacity by 68%.[15]

Extrapolation of humanity's Footprint for 2019, using partial data sets concluded that for 2019, global overshoot was at 73%. This data point was used to calculate Earth Overshoot Day 2019, which fell on July 29th.[16] Due to COVID overall demand fell in 2020 and Global Footprint Network estimated that overshoot fell to 53% for the first half of 2020. This pushed Earth Overshoot Day 2020 to August 22.[17]

Since the UN datasets do not include all aspects of consumption, the Footprint results are most likely underestimates. The data also doesn't document all depletion of nature's assets. As a result, the biocapacity numbers most likely overestimate the real situation. In consequence, humanity's actual overshoot is in all likelihood larger than what the National Footprint and Biocapacity Accounts document.

3b) Indices versus accounts

Accounts such as these are distinct from multi-dimensional indices (such as Environmental Performance Index, SDG-Index or Sustainable Society Index etc.), since the latter are, by nature, arbitrary scoring systems based on their architects' constructed aggregation approach (giving subjective weights to diverse aspects), rather than being driven by a clear, testable research question. Other accounts in the sustainability domain are (as distinct from multi-dimensional indices) GDP, greenhouse gas inventories, virtual water in trade, or the Living Planet Index. All of which emerge from clear research question.

Several metrics exist for assessing the material dependence or environmental performance of human economies. The primary ones are based on overall mass flows, greenhouse gases (in CO_2 equivalent, or sometimes only CO_2, typically expressed in tonnes per year), dollars, energy, biomass, land areas, bioproductivity, and planetary boundaries. Only accounting systems are

[15] For details, consult Global Footprint Network's National Footprint and Biocapacity Accounts 2019 edition www.footprintnetwork.org – key results at data.footprintnetwork.org ; for explanations, consult papers in the reference section. You can also download the free public data set, a rich, searchable workbook, from Global Footprint Network's webpage at https://www.footprintnetwork.org/licenses/public-data-package-free

[16] Earth Overshoot Day is calculated as the day in the year when human demand exceeds, for the year, what Earth can renew in the entire year. This means that the amount demanded that humanity demands from nature from January 1 to that day is as much as Earth renews in the full year.

[17] The report assessing Earth Overshoot Day 2020 is available here - https://www.overshootday.org/2020-calculation. Note that this assessment is built on extrapolation and partial data. It is only an estimate. The robust answer will be available in the 2024 edition of the National Footprint and Biocapacity Accounts.

discussed herein, i.e., metrics that are based on clear research questions and, hence, are built on clearly defined, testable aggregation principles. Therefore, this paper excludes indices with arbitrary aggregations, such as the Environmental Performance Index,[18] SDG-Index,[19] Human Influence Index,[20] Biodiversity Intactness Index,[21] and others. Such indices, while potentially useful in different contexts outside the domain of scientific inquiry, are not viable for comparing human demand against ecosystem regeneration, since they are not based on a clear research question and reflect their author's scoring preferences rather than scientific principles.

3c) Comparison to other measurement units to quantify human demand on nature

Other metrics also exist to measure human demand on nature. This section, building on Wackernagel et al. (2019), briefly explains the benefit of using biocapacity as the lens when comparing human demand against nature's capacity to renew.

- **Kilograms** can be used as a unit to measure mass flows. Describing mass flows of resources in kilograms (or more precisely in kilograms per year) seems precise. But there are several problems. **a)** Demand on nature per kilogram is vastly different between materials, and sometimes even for the same material. Consider the difference in the demand on nature of removing 1 tonne of water in a relatively wet country like Finland to 1 tonne of water in a relatively dry country like Jordan. Certainly, removing 1 kg of birds is of bigger significance then moving 1 kg of rocks. Further, when comparing biomass, there can be confusion between wet or dry weight. **b)** There is arbitrary exclusion. For instance, Material Footprint accounts exclude air and water flows. Furthermore, among other material flows it is not so clear what should be excluded or not. Ploughing? Moving trains? What about the roots of

[18] Esty, D.C.; Emerson, J.W. Chapter 5: From crises and gurus to science and metrics: Yale's Environmental Performance Index and the rise of data-driven policymaking. In Routledge Handbook of Sustainability Indicators; Bell, S., Morse, S., Eds.; Routledge: New York, NY, USA, 2018; pp. 93–102, ISBN 978-1-138-67476-9.

[19] Sachs, J.; Schmidt-Traub, G.; Kroll, C.; Lafortune, G.; Fuller, G. SDG Index and Dashboards Report 2018; Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN): New York, NY, USA, 2018; p. 476 or www.sdgindex.org . A paper on what the SDG Index obscures is here: Wackernagel, Mathis, Laurel Hanscom and David Lin (2017) Making the Sustainable Development Goals Consistent with Sustainability. Front. Energy Res. 5:18. doi: 10.3389/fenrg.2017.00018 http://journal.frontiersin.org/article/10.3389/fenrg.2017.00018/full

[20] Sanderson, E.W.; Jaiteh, M.; Levy, M.A.; Redford, K.H.; Wannebo, A.V.; Woolmer, G. The Human Footprint and the Last of the Wild. The human footprint is a global map of human influence on the land surface, which suggests that human beings are stewards of nature, whether we like it or not. BioScience 2002, 52, 891–904.

[21] Purvis, A.; Newbold, T.; De Palma, A.; Contu, S.; Hill, S.L.L.; Sanchez-Ortiz, K.; Phillips, H.R.P.; Hudson, L.N.; Lysenko, I.; Börger, L.; et al. Chapter Five-Modelling and Projecting the Response of Local Terrestrial Biodiversity Worldwide to Land Use and Related Pressures: The PREDICTS Project. In Advances in Ecological Research; Bohan, D.A., Dumbrell, A.J., Woodward, G., Jackson, M., Eds.; Next Generation Biomonitoring: Part 1; Academic Press: Cambridge, MA, USA, 2018; Volume 58, pp. 201–241.

the trees left in the forest? **c)** There are no clear upper limits for mass flows, reducing this approach's utility for measuring environmental limits. Some publications claim that eight tonnes of material Footprint per person and per year is a sustainable level,[22] but this number is based on a declaration not scientific deduction. For these reasons, assessments based on mass flow are not well suited to compare human demand against regeneration.

- **CO_2 emissions** include carbon dioxide released from burning fossil fuel, producing cement, or changing land-use patterns. **CO_2 equivalents** are broader as it aggregates all gases, including CO_2, on the basis of their global warming potential. Human induced emissions of carbon and other greenhouse gases are increasingly tracked given their growing climate impact and that their concentrations in the atmosphere are rising. Emissions can be compared to the upper emission limit, which in turn is a function of what temperature increase humanity is able to tolerate. Even with a temperature limit set by the Paris Agreement of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels",[23] there is great discrepancy in the literature about how much carbon is left to emit. Some, like NOAA, conclude that humanity is facing a *negative* budget if humanity wants to achieve the Paris goal.[24] Others, like Figueres et al.,[25] estimate a remaining CO_2 budget of between 150 and 1050 Gigatons. Given this uncertainty, and the fact that greenhouse gas emissions are not the complete set of competing demands on the biosphere, emissions of CO_2 or CO_2 equivalents are also not fit to fully answer the question of how much people use compared to how much Earth's ecosystems can regenerate.

- **Monetary currencies**, such as US dollars or Euros, are useful as an accounting unit for comparing human activities but cannot link human demand to biological regeneration. As the value of dollars can change from year to year due to inflation, accounts can also be expressed in constant dollars. Further, the same financial amount represents dissimilar values to different people. This is recognized by UNDP / United Nation Development Programme's Human Development Index (HDI). There, the income dimension, one of the index's three pillars, is measured as the logarithm of people's financial income. (The other

[22] Lettenmeier, M.; Liedtke, C.; Rohn, H. Eight Tons of Material Footprint—Suggestion for a Resource Cap for Household Consumption in Finland. Resources 2014, 3, 488–515. Or Stefan Bringezu. Visions of a sustainable resource use. pp. 155–215 in Bringezu, S., Bleischwitz, R., Eds, 2017. *Sustainable Resource Management: Global Trends, Visions and Policies*. Routledge: New York, NY, USA, 2017, ISBN 978-1-906093-26-6.

[23] UNFCCC Paris Agreement 2015. https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[24] Butler, J.H.; Montzka, S.A. The NOAA Annual Greenhouse Gas Index (AGGI); NOAA Earth System Research Laboratory: Boulder, CO, USA, 2020. https://www.esrl.noaa.gov/gmd/aggi/aggi.html

[25] Figueres, C.; Schellnhuber, H.J.; Whiteman, G.; Rockström, J.; Hobley, A.; Rahmstorf, S. Three years to safeguard our climate. Nature 2017, 546, 593–595. https://www.nature.com/news/three-years-to-safeguard-our-climate-1.22201

two pillars are longevity and access to basic education[26]). Additionally, the same monetary unit can purchase different amounts of goods in different markets. Monetary amounts can be made comparable by adjusting them according to their purchasing power. This translation is called purchasing power parity [ppp]. Any currency can be converted into other countries' local currency, with conversion rates changing daily. Still, with all this variance, monetary units, in local currencies or expressed in US Dollars, can be a useful measure of comparison at the micro scale. For instance, it can reveal social preferences such as pursued by The Economics of Ecosystems and Biodiversity (TEEB) when comparing project options in their effort to 'mainstream the values of biodiversity and ecosystem services into decision-making'. However, financial assessments do not compare resource use against regeneration. Moreover, at the macro level, financial metrics become problematic, as dollars reflect market preferences, not ecological necessities or regeneration. The two leading studies that financially value natural capital at a macro scale vastly underestimate the significance of natural capital vis-à-vis other capital assets. They are *Changing Wealth of Nations* by the World Bank (2011/2018), and *Inclusive Wealth Report* by UNU (2012/2018). The former study concludes that the value of the planet, as a percentage of humanity's total assets, only accounts for 9% of humanity's total wealth. This number is implausibly low given that all wealth depends on natural capital, and there is wide recognition that the planet's natural capital is overused. These financial valuations do not recognize the importance of ecosystem regeneration in meeting humanity's material demands.

- **Energy units** can be defined precisely and measured in a lab but are highly ambiguous for describing flows through ecosystems or societies because of entropy cascades. For instance, the sun's 175,000 TW (or Terawatt) of solar radiation onto Earth generates approximately 70 TW of Net Primary Productivity (NPP) on the land and more if including the NPP of the oceans (half of that NPP is currently used to produce about 1 TW of food)[27]. Of the land-based NPP, 1/3 or more is used for generating about one TW of food calories for people.[28] This energy cascade illustrates the stark difference of one TW solar radiation and one TW of food. Thus, energy, as common denominator, can lead to confusion. The closest to a consistent energy accounting approach that includes the quality of energy is Odum's

[26] United Nations Development Programme 2016 Human Development Report: Human Development for Everyone; 2016. Or United Nations Development Programme. Human Development Indices and Indicators: 2018 Statistical Update; United Nations Development Programme: New York, NY, USA, 2018; p. 123.

[27] This is based on the calculation that the global Food Footprint as assessed by Global Footprint Network's MRIO analysis indicates that Food consumption occupies a Footprint of slightly more than half of the planet's biocapacity.

[28] Haberl, H.; Erb, K.-H.; Krausmann, F. Global human appropriation of net primary production (HANPP). Encycl. Earth 2013.
https://editors.eol.org/eoearth/wiki/Global_human_appropriation_of_net_primary_production_(HANPP)

eMergy calculation.[29] However, the commonly published conversion factors ('transformaties') that translate final use back into solar input are not robust.[30]

- **Biomass balances** (whether expressed in tonnes of carbon, dry matter, or energy content) as used in Net Primary Production (NPP) assessments and the complementary Human Appropriation of NPP (HANPP) are very closely related to the question of human demand and regeneration.[31] The challenge is that demand as measured by HANPP cannot be compared with clarity to available regeneration, nor can a sustainable level of NPP extraction be clearly defined, let alone measured. Studies that compare the two come up with wide ranges of answers, for definitional reasons, as well as measurement challenges.[32] While NPP assessments are undoubtedly an important tool, particularly to evaluate intensity of biological uses, [33] they have limited power to robustly track demand against regeneration. **Note**: Ecological Footprint accounting builds on NPP approach, by taking a more agricultural perspective. This means it focuses not on all plant matter but on the particular kind that is demanded by people. For instance, timber demand can be compared with sustainable yields for timber of forests. By using this agricultural lens, it is possibly to offer sharper comparisons between demand and regeneration. Ecological Footprint accounts can also be more comprehensive than NPP assessments as they also include greenhouse gases (or at least CO_2 from fossil fuel and cement production in the case of the National Footprint and Biocapacity Accounts). Agricultural comparisons also become more meaningful across land types. For instance, crop land is typically the most productive land, but it is not managed for highest net primary productivity, therefore undervalued in NPP accounts.

[29] Odum, H.T. Environmental Accounting: Emergy and Environmental Decision Making; Wiley: Hoboken, NJ, USA, 1996; ISBN 978-0-471-11442-0. Or Brown, M.T.; Ulgiati, S. Emergy and Environmental Accounting. In Encyclopedia of Energy; Cleveland, C., Ed.; Elsevier: New York, NY, USA, 2004.

[30] The numbers provided in the eMergy literature estimate the embodied solar energy in various flows through ecosystems and the human economy. Given the massive energy cascade from sun to product, assumptions for such calculations are often heroic, For instance, the eMergy attributed to wind seems excessively high.

[31] Haberl, H., Wackernagel, M., Krausmann, F., Erb, K.-H., Monfreda, C., 2004. "Ecological Footprints and Human Appropriation of Net Primary Production: A Comparison." Land Use Policy, 21 (2004) 279–288.

[32] Rojstaczer, S.; Sterling, S.M.; Moore, N.J. Human Appropriation of Photosynthesis Products. Science 2001, 294, 2549–2552. https://science.sciencemag.org/content/294/5551/2549

[33] Measuring in addition to Footprint extension the intensity of use of those areas complements Ecological Footprint accounting, which only tracks mutually exclusive areas. In other words, it would be valuable, once an Ecological Footprint assessment is done, to further evaluate each component on the intensity of use. One particular "intensity" angle could be "biodiversity friendliness" of the occupied area. For instance, a mono-cropping area may be highly productive, but devastating for biodiversity. In contrast, sustainably harvested forest that also include high biodiversity value as part of their management scheme may represent a benign use of areas. The former could be colored a red Footprint, and the latter a green one.

- **Hectares** can be used to compare human demand for productive hectares to hectares available. Unfortunately, not every hectare represents the same biological productivity: just consider the biological productivity of one hectare of a rocky mountain slope, a tundra forest, a tropical rain forest, or a highly fertile cropland in river basin.

- **Global hectares** are productivity adjusted hectares. Each unit represents a biologically productive hectare with world average productivity. This equivalence makes the unit convenient for biocapacity accounting.[34] Biocapacity is the biologically productive area that provides ecological services. All human demands on those surfaces that compete for space can therefore be added up. This more agriculturally-based metric is straightforward. It builds on established agronomical practices to measure harvested crops and yields. As productivity changes annually (because of technological innovations, climate change, shifts in management practices, etc.), the global hectare changes accordingly. The sum-total of productivity-adjusted areas representing all of people's competing demands on nature then be compared against available areas (also expressed in productivity adjusted hectares).

In conclusion: among all the discussed approaches that map human demand on nature using differing lenses, biocapacity accounting based on "global hectare units" seems to be the most relevant metric for comparing human demand against ecosystem regeneration. In fact, the ability to map human demand ***against*** ecosystem regeneration stands out as the Ecological Footprint accounting particularly useful advantage.

But there are also very complementary approaches, two of which are discussed in 3d) below.

3d) Complementary approaches: Planetary Boundaries and Doughnut Economics

The **Planetary Boundaries**[35] approach identifies key physical conditions that are needed to maintain the integrity of the biosphere. It identifies nine environmental areas where transgressions could lead to shifts that would irreversibly move the biosphere out of the stable conditions which characterized the Holocene ("tipping points"). They are:

- Stable climate
- Intact biodiversity
- Sufficient nutrients (but no overload)

[34] Wackernagel, M., A. Galli, L. Hanscom, D. Lin, L. Mailhes, T. Drummond (2018), CHAPTER 16: Ecological Footprint Accounts: Principles" p244-264, in Simon Bell and Stephen Morse (Editors) 2018. *Routledge Handbook of Sustainability Indictors*, Routledge International Handbooks. For a draft see here.

[35] Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S., III; Lambin, E.F.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. 2009. A safe operating space for humanity. *Nature*, 461, 472–475. www.nature.com/articles/461472a **Also**: Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; de Wit, C.A.; et al. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science*, 347, 1259855. https://science.sciencemag.org/content/347/6223/1259855

- Protective ozone layer
- Absence of pollutants
- Clean and sufficient fresh water
- Stable and fertile soils
- Absence of acidification in both water and soils

These are the necessary conditions for healthy, productive ecosystems that can maintain their integrity. Hence, they enable the biosphere's ability to regenerate, i.e., its "biocapacity". For each condition (or each of the 9 "planetary boundaries"), the Planetary Boundaries approach employs metrics. Typically, they compare flows, but they can also address stocks – like current concentration of greenhouse gases compared to what is tolerable by the biosphere without triggering a phase shift. This means that these metrics do not measure regeneration per se, but attempt to identify the distance from "a safe zone".

In contrast to Ecological Footprint accounts, the Planetary Boundaries approach does not offer an aggregate measure to show the compound effect, or trade-offs among those nine domains. Nor is this approach geographically explicit. While biocapacity can be scaled down to every single hectare, Planetary Boundaries makes the case for the biosphere as a whole system.

Still, the Planetary Boundaries approach is related to the question of how big the human demand is compared to ecosystem regeneration, but does not offer an overarching metric to provide an overarching quantification beyond warning signs for each domain, and that only at the planetary level.

Doughnut Economics, introduced by Kate Raworth, has playfully advocated for a "safe and just operating space." This refers to a way of living that is ecologically safe by not overusing the planet, while also providing a fair and equitable opportunity for all to thrive. She depicts the sustainable development challenge as a two-dimensional doughnut, the inner edge representing the minimal social foundation and the outer edge the upper ecological ceiling.[36] Therefore, the inner part of the doughnut corresponds to the "safe and just operating space," the same space depicted as the blue "global sustainable development" box in the upper right corner of the HDI-Footprint diagram. The clever depiction of a doughnut inspired Raworth to proclaim "doughnut economics," an economic theory that has the goal of supporting human wellbeing within the constraints of our planet.

There is no specific metric associated with Kate's doughnut. Often she refers to Planetary Boundaries as the upper one and a multi-dimensional wellbeing metric for the inner one. The

[36] Kate Raworth. 2017. Doughnut Economics: Seven Ways to Think Like a 21st Century Economist. Chelsea Green Publishing.

HDI-Footprint diagram is useful as it allows to depict results for cities, individuals, or countries, as well as trends over time.[37] It also represents all four possibilities (low/high Footprint, low/high wellbeing), while the doughnut only shows three of those (inside inner circle, between circles, outside outer circle). The forth one (high Footprint, low well-being), potentially the most tragic one in the context of securing wellbeing for all within planetary constraints, does not appear in the doughnut.

[37] Note that the simplicity of the doughnut leaves out some possible combinations. In reality, there are four possible states: low/high Footprint, low/high wellbeing makes four possible combinations. In this case, low Footprint per person would be one lower than the biocapacity available on the planet per person.
The doughnut only depicts three of them (inside inner circle = low well-being & low Footprint; between circles = high well-being & low Footprint; outside outer circle = high well-being & high Footprint). The forth one (high Footprint, low well-being), potentially the most tragic one in the context of securing wellbeing for all within planetary constraints, does not appear in the doughnut. However, according to the HDI-Footprint analysis, it is increasingly common for countries to be in that quadrant.

SECTION 4: Strengths and limitations

Main Advantages of Ecological Footprint Accounting

- Ecological Footprint accounts are an established methodology: they are based on simple accounting principles. The accounts have been produced and updated for over 25 years, and have matured significantly, both with regards to data sources and accounting methodology.
- There is power in using biology as a sustainability lens. A biological view of the world as promoted by Ecological Footprint accounting, planetary boundaries, or similar approaches builds on the insight that the biosphere's power to regenerate has become too small compared to human demand, leading to climate change, biodiversity loss, water scarcity, etc. Explaining the challenges from this biological perspective has various advantages:
    - This biological approach joins all the human pressures – from water, climate, biodiversity, food, energy, etc. – under one roof. This enables us to solve them all together (rather than one at the cost of another one.). This all-encompassing view also helps build the needed bridge between conservation and climate change.
    - Biological metrics are understandable. Very few relate to 2°C, ppm, or tons of carbon (or is it CO_2?). In contrast, even primary school kids understand biological balances (how much we take compared to how much is being renewed), or as done in the case of Ecological Footprint accounting, expressing results in number of Earths, number of countries (Switzerland uses 4 Switzerlands), the Earth Overshoot Day date, or hectares.
    - The biological lens reveals “skin in the game”. In contrast to the ‘carbon-only’ view, a biological approach makes the company, city, or country’s economic self-interest clear and obvious. It emphasizes resource security and the risk of not being prepared to each country as resource availability diminishes. To use a blunter analogy, visualizing the emergency as a “storm”, it makes little sense to argue: “I will only fix my boat if others fix their boat first”, yet that is the dominant strategy in the current climate “negotiations”. A more comprehensive biological approach helps see climate action as necessary for one’s own success, rather than merely noble, i.e., a good deed for humanity. The current climate debate is based overwhelmingly on a “noble argument” (“it is our responsibility to humanity and the future”), leading to timid action. In reality, a country’s competitiveness and success depends on aggressive climate action, preparing itself for an inevitable carbon-free future, thereby strengthening its own

resource security (and also, as a side benefit, supporting humanity's sustainability).

- The accounts are of policy relevance because they focus on the most limited resources (biological regeneration or biocapacity) and indicate the overall biocapacity demand of societies compared to resource availability on the planet, or in a region. They directly respond to the European Commission's goal of "living well, within the limits of our planet." Given the climate goal of the Paris Agreement and IPCC's recognition of the need to rapidly phase out of fossil fuel use, the only viable pathway for the future is a regenerative economy that lives off the planet's biocapacity rather than off further depletion. Planning for such an economy requires careful accounting of biocapacity for each country. Recent IPCC and IPBES reports confirm the importance of looking at climate in the context of all demands on the biosphere.
- Geographical and temporal coverage: the indicator has a global coverage and data is available over a long timescale (1961-2016 and updated annually – for some countries, now-casts are available too on request). The core data, strictly based on UN and UN-affiliate sources, is national and allows for aggregations at different physical scales. The indicator can be disaggregated to provide information on specific resources or ecosystems.
- The accounts have been tested by over ten national government agencies. For instance, in 2018 the Swiss Ministry of Environment released its latest review where they recalculated the Swiss results for the time period of 1996 to 2015 and replicated Global Footprint Network results within 1-3% (BAFU, p. 87).
- The Ecological Footprint has reached a wide range of audiences to increase understanding of the size of the human economy compared to the planet. It has also helped to identify the options that exist to reduce people's demand on nature. For example, Earth Overshoot Day 2019 (www.overshootday.org), based on Ecological Footprint accounting, generated over 4 billion documented media impressions, with much reporting on how people can #MoveTheDate.

Main Limitations of Ecological Footprint and Biocapacity Accounting[38]

Several important aspects of sustainable use and management are not measured by the Ecological Footprint or by biocapacity, largely because they are not part of the research question driving the accounts:

[38] For a discussion of limitations also consult European Environment Agency (2020): Ecological footprint of European countries. www.eea.europa.eu/data-and-maps/indicators/ecological-footprint-of-european-countries-2

- **Non-ecological aspects of sustainability**: having an Ecological Footprint smaller[39] than the biosphere is a minimum necessary condition for a sustainable society, but it is not sufficient. For instance, the Ecological Footprint does not consider social well-being. In addition, on the resource side, even if the Ecological Footprint is within biocapacity, poor management still can lead to depletion. An Ecological Footprint smaller than biocapacity is merely a necessary condition for making quality improvements replicable and scalable.
- **Depletion of non-renewable resources**: the Ecological Footprint does not track the amount of non-renewable resource stocks such as oil, natural gas, coal, or metal deposits. The Footprint associated with these materials is based on the regenerative capacity used or compromised by their extraction and, in the case of fossil fuels, the area required to assimilate the wastes they generate.
- **Inherently unsustainable activities**: activities that are inherently unsustainable, such as the release of heavy metals, radioactive materials, and persistent synthetic compounds (e.g. chlordane, PCBs, CFCs, PVCs, dioxins, etc.) do not enter directly into Footprint calculations. These are activities that need to be phased out independent of their quantity (there is no biocapacity budget for using them). Where these substances cause a loss of biocapacity, however, their influence is tracked by complete Footprint and biocapacity accounts, as long as data picks up this damage.
- **Ecological degradation**: The Ecological Footprint does not directly measure ecological degradation, such as deforestation, soli loss, or increased soil salinity from irrigation, which could affect future bioproductivity. However, if degradation leads to reductions in biological productivity, then this loss is captured in subsequent annual measurements of biocapacity. Aggregate numbers also hide local overexploitations in one area that are compensated by 'under exploitation' in another one.
- **Resilience of ecosystems**: Footprint accounts do not identify where and in what way ecosystems are vulnerable or resilient. The Footprint is merely an outcome measure documenting how much people demand compared to what the biosphere regenerates.

[39] The question also his how much smaller than the entire regenerative capacity of the planet human demand should be. For instance, Prof. E.O. Wilson suggest to leave half the planet's capacity to wild species which might give us a chance to safeguard 85% of the world's biodiversity. For more details see: Wilson, E.O. 2016. *Half-Earth: Our Planet's Fight for Life*. Liveright Publishing Corporation, New York. Or https://www.half-earthproject.org

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SECTION 5: How the robustness of the accounts is being improved

As discussed in the introduction, the Ecological Footprint approach, and the National Footprint and Biocapacity Accounts in particular, have gained from feedback, suggestions, and criticisms. This section explains some additional improvements that have emerged from such feedback.

It also explains how the National Footprint and Biocapacity Accounts are being taken to the next level of rigor and robustness. Essentially they are becoming an independent organization in its own right: www.FoDaFo.org

Examples of improvements in the past and hopes for the future

The National Footprint and Biocapacity Accounts are constantly evolving. Many of the changes are minor, reflecting better data, small improvement in accounting procedures, etc. In fact, the research team is maintaining a data base on all possible improvements, including minor ones that are making the implementation cleaner and clearer.

In addition to the introduction of global hectares or the shift on how nuclear energy is included in the National Footprint and Biocapacity Accounts (as discussed in Section 1), there have been many other methodological improvements. They include:

- revising the world average carbon sequestration by forests (which turned out to be lower than what we previously estimated),[40]
- detailing trade flows, and
- changing procedures in fish trade to reduce the noise in the data.

There are also many aspects that need attention and refinement.

- **Equivalence Factors:** There are several legitimate criticisms related to this key aspect of Ecological Footprint accounting. For instance, it would take more research to verify how well pixels of land with high suitability from GAEZ match with crop land. It may not be totally accurate to assume that the most suitable land must be used as cropland. More research could be done to compare and contrast the suitability index map with land cover map. Our preliminary assessments indicated that there is room for improvement. Also when assessing the value of built-up area, the assumption that for most cities, built up area sits on (potentially the best) crop land, holds in many places. But there are also many modern cities, such as in the gulf states, where cities are built on desert areas. In

[40] Mancini, M. S., Galli, A., Coscieme, L., Niccolucci, V., Lin, D., Pulselli, M., Bastianoni, S. and Marchettini, N. 2018. Exploring ecosystem services assessment through Ecological Footprint accounting. Ecosystem Services, 30, 228-235.

those cases, adjustments should be made (as the National Footprint and Biocapacity Accounts already do for the UAE, based on more detailed local analyses with UAE counterparts).

- **Potential vs. Actual Biocapacity:** we are not clear ourselves about the BC definition and this lack of clarity is perceived (by some, true – not by many) by possible users. Whether biocapacity should refer to productivity under "sustainable" practices or under "actual and current management practices" is highly debated topic in Ecological Footprint related critical papers.

- **Time-delay in results:** the focus on using UN data for the National Footprint and Biocapacity Accounts has led to a time gap of 4 years between results and the present. This make the results significantly less useful for policy debates. We have responded by developing some now-casting capabilities. These capabilities have room for refinement. To make them more rigorous additional data points can be used that complement the UN data set.

- **Data standards:** our accounts use SITC rev.1 coding to be able to trace trends back to 1961. This is an outdated standard, and as a result our numbers do not match with the categories of more modern trade analysis.

- **Forest Footprint:** here many improvements are possible, including distinguishing between hardwood and softwood, finding ways to have time-trends in forest productivity (FAO does only report static numbers). The impact of pests and forest fires, and how they are changing over time could also be analysed in more detail.

- **Grazing Footprint**: Estimating the intensity by which grazing areas are used (or overused) could also be improved, including finding more adequate data sources.

- **Fisheries Footprint**: even though it is well recognized that fisheries around the world are under stress, and data is getting richer, it is still difficult to robustly estimate harvest against regeneration for all fisheries around the world. The National Footprint and Biocapacity Accounts use www.SeaAroundUs.org data, which is the leading source.

The list continues, and clearly there are many additional arenas that would benefit from further research. This includes finding ways to track forest productivity over time, to distinguish between hard soft wood, to map water use against biocapacity, to develop ways to capture grazing land overuse, track erosion or groundwater depletion. Greenhouse gases could be included more fully; deeper assessments could help evaluate the margin of errors the accounts inherently carry.

Building a new organization for the National Footprint and Biocapacity Accounts (FoDaFo)

Global Footprint Network and York University have joined forces to establish FoDaFo (Footprint Data Foundation) – Footprint Initiative with York University. It was legally established in Canada in 2019.

The rationale is simple: By establishing the National Footprint and Biocapacity Accounts within an independent and respected academic network, the Accounts will become neutral and robust. This means they need to be more robust through increase scientific engagements, better governed to have a clean process of improving the accounts, and more transparent so all can test them. All this is needed if those accounts should become an even more effective and trusted reference for decision making in support of sustainability.

To overcome misconceptions and scepticism, the world needs a credible, neutral body that develops and makes these national results available. The source also needs to be able to engage with potential criticism and learn from it.

FoDaFo aims at:

1. Producing and maintaining, with the help of academic institutions, the National Footprint and Biocapacity Accounts derived from solid and trusted data sources and assembled with academic rigor, to ensure they are robust, objective, independent. They should be released on an annual basis.
2. Establishing an international collaboration of researchers who drive the Accounts' improvements. This enables tapping into creative research minds from around the world in order to improve weaknesses of the accounts and find innovative ways to better address the research question of the Ecological Footprint accounts.
3. Gathering a consortium of governments and institutions who contribute to and draw upon the Accounts and adopt them as a key tool in their own decision-making.
4. Training a growing pool of researchers skilled in Footprint accounting who can apply their skills and knowledge to advance a world where all can thrive within the means of our planet.
5. Building robust governance is not only needed for the organization itself. Governance is also required to guide the scientific decision-making on how to manage and improve the National Footprint and Biocapacity Accounts. For this reason, FoDaFo has established a science advisory committee that has as its primary task to evaluate potential improvements proposed by scientists and then to recommend, after testing, which ones are fit for implementation. Such a set up allows for open academic engagement as outside researchers can freely engage in research on methodological improvements,

employing their fullest creativity. At the same time, by carefully selecting which improvements are truly fit for implementation, the science advisory committee also makes sure that the actual accounts stay consistent and stable. In addition, the science committee will also develop a research agenda to help researchers focus on the most critical tasks that need to be improved.

The website www.FoDaFo.org provides more background on the effort.

SECTION 6: List of common criticisms, including “Why not just focus on carbon?”

THE FOLLOWING ARE OUR RESPONSES TO ACTUAL CRITICISMS WE HAVE RECEIVED:

1) CRITICISM: "The Ecological Footprint of a person to satisfy his or her consumption includes demands for food, fiber, timber, space occupied for built infrastructure, and the space required to assimilate waste, including emissions from burning fossil fuels. Currently, the most significant component of humanity’s Ecological Footprint is the carbon foot”rint." This is highly misleading [because] yo“ say "the space required to assimilate waste, including emissions from burning fossil”fuels", but, in fact, the only thing the ecological footprint calculates is the fossil fuels component. It considers no other”waste" (from e-mail correspondence).

OUR RESPONSE: Let us make a distinction first: a) there is the Ecological Footprint in theory, if you had all the data. Then b) there is the Ecological Footprint in practice, the application, limited by existing data. Further c) even more limited: The National Footprint and Biocapacity Accounts. They are even more constrained in what they can cover because we deliberately build them on official UN data, so we cannot be accused of bias in picking data.

As a result of this approach, the National Footprint and Biocapacity Accounts, as stated in the literature, produce, with high likelihood, UNDERESTIMATES of actual biocapacity deficits. For instance, on the biocapacity side, losses are not included (such as soil erosion, deforestation, groundwater depletion). Hence the real biocapacity is even smaller than our estimates. On the Footprint side, not all demands are included because not all are documented in UN accounts. Hence the real footprint is larger.

Yes, you are correct, currently the largest waste stream considered in the National Footprint and Biocapacity Accounts based on UN data is carbon emission from fossil fuel.

It is also important to note, all the efforts that make up managing urban waste (freshwater cleaning, wastewater cleaning, garbage collection and management, even incineration) are included as long as UN data sets captures them adequately. Most of it is carbon footprint, and some is built-up footprint. The accounts also implicitly include agricultural land to absorb waste from domestic animals (which also serves as a fertilizer for that land). Since this function is part of a cycle on land that also produces feed and food, counting this waste absorption would be double counting.

Maybe you might argue that given these limitations, the results still are “highly misleading”. But what would constitute “highly misleading,” is it misjudgements by 5%, 50%, or 500%? How

vastly are Ecological Footprint accounts missing the true nature of the human metabolism? And what is the evidence?

2) CRITICISM: "The most significant component of humanity's Ecological Footprint is the carbon foo"print", which is a drastic understatement, because it is the change in the carbon footprint that exclusively generates overshoot." (from e-mail correspondence).

OUR RESPONSE: According to the accounts, currently (i.e. 2020) 57% of humanity's Ecological Footprint is carbon. 200 years ago it was zero; hopefully before 2050 it will be zero (and that would be needed in order to comply with the goal set in the Paris Agreement).

Note: it is possible to have overshoot locally; and this has occurred throughout human history (overharvesting a forest, for example). Global overshoot results from the sum of the total demand exceeding the sum total of planetary regeneration, not from one single thing. For example, if humanity used half the amount of fossil fuel of today, and NOTHING ELSE, there would be enough biocapacity to neutralize the emissions and humanity would NOT be in overshoot. However, this would leave us without food and fibres. Just using half of fossil fuel would currently occupy 38% of the biosphere. So it is incorrect to say that one portion of the Ecological Footprint is contributing to overshoot and the other portion does not. It is the sum-total.

Let's use a financial example: If you do overspend your financial budget, it would not make sense to say "this Euro does not count towards my overspending but this one did count." You overspend because the sum of all your Euros spent exceeds the sum of all your Euros earned. How else would you apply the logic of your criticism to monetary accounts?

Additionally consider this: Global Footprint Network is not advocating that human demand should be "one planet." As E.O. Wilson points out, if we want to avoid 85% of biodiversity from going extinct, it may mean that we should limit humanity's demand to ½ planet. How much would you, dear reader, allocate for biodiversity preservation?

3) CRITICISM: "The fact that footprint articles appear in the scientific literature does not prove that they are of quality, given that the peer review process is highly fallible. To find out the real arguments, we must go to the critical articles like:

Van den Bergh, J. C., & Verbruggen, H. (1999). Spatial sustainability, trade and indicators: an evaluation o' the 'ecological foo'print'. *Ecological Economics*, 29(1), 61-72.

Ayres, R. U. (2000). Commentary on the utility of the ecological footprint concept. *Ecological Economics*, 32(3), 347-349.

Fiala, N. (2008). Measuring sustainability: Why the ecological footprint is bad economics and bad environmental science. *Ecological Economics*, 67(4), 519-525.

Galli, A., Giampietro, M., Goldfinger, S., Lazarus, E., Lin, D., Saltelli, A., Wackernagel, M. & Müller, F. (2016). Questioning the ecological footprint. *Ecological Indicators*, 69, 224-232. "
(from e-mail correspondence).

OUR RESPONSE: Yes, we are well aware of those, and last one we participated in. To be fair, the same logic of "fallibility of the review process" equally applies to criticism published in the scientific literature.

So we need to look at the actual arguments. Additionally, because of the fallibility of the scientific review process, Global Footprint Network encouraged reviews by the most important users: national governments. We have encouraged national agencies to check whether the numbers the National Footprint and Biocapacity Accounts produce are robust and consistent. Those who did reviews of the accounts confirmed the consistency and reproduced our results within small margins of differences.

4) CRITICISM: "A press release stated: 'If every person on the planet lived as a Portuguese average person, humanity would demand more than 2 planets to sustain its resource needs. This would imply that the productive area available to regenerate resources and absorb waste globally.' But the ecological footprint does not in fact consider 'natural resources' (implying that it considers them all or at least the generality), but only and exclusively the area directly used for human activities (agriculture, forestry, urbanization, etc.) and the potential area needed to remove excess carbon dioxide from the atmosphere." (from e-mail correspondence).

OUR RESPONSE: Correct, Ecological Footprint accounting focuses on biological resources. Also in as far other natural resources (such as fossil fuel) put a demand on biological resources. And the more precise answer is: demand on the regenerative capacity of the planet. We would not call it the "potential area needed" but the actual area needed. If there is overshoot, not all of it may exist, it is an actual demand nevertheless.

5) CRITICISM: “It is primarily this misleading aspect of the way in which the ecological footprint is reported that undermines its credibility.” (from e-mail correspondence).

OUR RESPONSE: This is an important point. It is important to communicate with clarity. And it is a compromise of using understandable language rather than being overly technical and losing audiences. Sometimes the simplified communications do not convey all the sophistication of the underlying accounts. Still saying that humanity is demanding 70 percent more than what Earth renews, or that it would take two full Earths to provide for a world where the entire humanity consumes at the level of Portuguese (while also acknowledging that this assessment might be an underestimate) is pretty accurate.

6) CRITICISM: “Whenever I have seen criticisms (or have made them myself) of the ecological footprint, the answer is based on its communication effectiveness. This raises several fundamental questions for me, including: when the environmental mo’ement's rallying c“y is "listen to the scie”tists" do we really want to use an indicator whose only (undeniable) merit is its communicability?” (from e-mail correspondence).

OUR RESPONSE: It would be absolutely wrong to use such an indicator if communication prowess was its only merit. However, Global Footprint Network does not make that case for the footprint solely based on its “communication effectiveness.” If that were the case, this would be a big problem. Of course, first of all, the data and research question needs to be clean and clear. We have made the case that Ecological Footprint accounting performs well in this regard.

In addition to having robust research, you also need to be able to communicate it in a meaningful way. It may be useful to investigate how well other metrics are faring on both accounts, and how this compares with Ecological Footprint accounting (For more details, consult this open-access paper: it details how Footprint accounts build on a specific research question, linked to simple, robust principles). And yes, the results also communicate effectively.

In contrast, for instance, there are many multi-dimensional indices in the sustainability space that do not even have a research question (we could easily provide you with a list of at least ten prominent ones). Or some accounts use measurement units that are ambiguous, and ultimately less fit than “global hectares” for comparing human demand to ecological regeneration. For more details on this issue, please consult section 2.1 of the open access paper https://www.mdpi.com/2071-1050/11/7/2164

7) CRITICISM: "Why not use each c'untry's carbon budget consum–tion - also clearly communicable (allowing us to communicate whether we are above or below the border, and also allowing us to identify a carbon overshoot day), but without distortions and with much greater scientific basis?" (from e-mail correspondence).

OUR RESPONSE: Of course you can, and many do. What is the question you want to answer? If you want to compare demand with availability, just focusing on carbon may be tricky. Yes, emissions are more straightforward to track, at least conceptually. But what is the budget, i.e., how much emission is available? Here you have to make a number of assumptions. Do you base the budget on policy choices (policy goals of your jurisdiction)? Or based on a global temperature goal as set by the Paris Agreement (but then what is the share for your jurisdiction?) Is there even an emission budget left? (450 ppm CO_2 equiv may give us a 66% chance never to exceed 2°C global warming, according to IPCC's 2014 report, yet NOAA tells us that we have exceeded 500 ppm CO_2 equiv last year– hence there may be no budget left)…

Since the only possibly future is regenerative – why not track human demand against the regenerative budget? (we call that budget biocapacity). Also, is it really possible to get out of carbon without increasing the pressure on the rest of the biosphere?

In Ecological Footprint accounting, both sides are quite clear: How much is your demand? How much is regeneration. In the carbon world, the second one is not clear at all for reasons mentioned above.

In essence, whether humanity decarbonizes proactively, or eventually runs out of exploitable fossil fuels (leaving a massive greenhouse gas debt in the atmosphere), humanity will inevitably have to live off our planet's regeneration, not its liquidation. The earlier humanity transforms, the more of our planet's regeneration capacity will be left. This means, the swifter humanity curbs and then eliminates its fossil fuel demand, the easier it can fit within the planet's regenerative resource budget. Decarbonizing will take focus and willpower, since fossil fuel allowed people to overcome and extend the planet's biological income. Fossil fuel is powerful. For instance, it:

- boosts food and feed production thanks to fertilizers, pumps, and tractors (and enables storing, processing and shipping that food and feed around the world, overcoming local food production limitations);
- substitutes many biological fibres (now 70% of fibres used are synthetic);
- heats more houses without burning wood; and
- gets people around without feeding horses and donkeys.

8) CRITICISM: "The lack of caveats in Ecological Footprint dissemination is worrying and has led to the most serious criticism of the method to date, that of it fulfilling the criteria for pseudo-science for failing to disclose uncertainties in calculations and results." Johannesson et al. 2020

OUR RESPONSE: Yes, it is important to be clear about exactly what is being measured (including being explicit about the precise research question), and what the limitations of the research and metric execution are.

In our scientific publications, we address the issue of reliability as much as we can. But like anybody using official statistics, whether from national or UN sources, the numbers used as inputs into our accounts are provided without confidence intervals. This is true in other domains as well. For instance, when GDP, longevity, or unemployment figures are presented, they also do not provide information about potential margin of error.

It is challenging to estimate what the margin of error may be of the results stemming from the National Footprint and Biocapacity Accounts. We have good reasons to believe that the biocapacities we report are an exaggeration and the Ecological Footprints underestimates. But this is certainly an area more research could be useful.

9) CRITICISM: "For instance, it is not clear why it is useful to convert greenhouse gases to land as methane and nitrous oxide are already aggregated into CO2 equivalent indicators of greenhouse gases." Fiala, 2008

OUR RESPONSE: As documented elsewhere, we consider biological regeneration to be the overarching physical constraint for the human economy. Similar to the argument that heating of the planet is not driven by just CO_2, but also other greenhouse gases. We take this argument to the next level pointing out that over-demand is not just driven by food, or energy or timber use, but by the sum total of all those demands combined.

If you recognize that the physical challenge we face is not just climate change, but all overshoot issues combined, then it may be helpful to turn to Ecological Footprint accounting.

10) CRITICISM: "For land degradation though, the benefits of looking directly at soil erosion rates are obvious as the ecological footprint gives no information on this." Fiala, 2008

OUR RESPONSE: Yes, if you just want to measure soil erosion, don't use Ecological Footprint accounting. Also note that National Footprint and Biocapacity Accounts do not capture soil erosion (apart from declining productivity over time) since UN data sets are not sufficient to bring that aspect into the accounts. For more specific Ecological Footprint studies, if adequate

data exists, erosion can be incorporated into the accounts – with the benefit of putting erosion in context with many other demands on the biosphere.

Note: Do not turn to Ecological Footprint and biocapacity results when addressing a narrow issue that you have already clearly identified. RATHER: Apply Ecological Footprint accounting when you need a fresh approach to interconnected problems that need systemic and cross-sectoral solutions.

11) CRITICISM: "The Ecological Footprint converts flows of energy and matter to and from economic activities in **hypothetical** land area (in ha or s35ilometresmeters [km2]) that would be needed to sustain these flows. Yet, the possibility exists that this is interpreted as realistic or, worse even, actual land area. We refer to this first concern about the Ecological Footprint method as 'false concreteness'." Van den Bergh and Grazi, 2013

OUR RESPONSE: The Footprint measures material demands by people that compete for biologically productive space. This is then compared to the amounts of such space available. If more is used than is regenerated, overshoot occurs. The difference that is not provided by regeneration comes from depletion.

One demand on productive areas comes from excessive CO_2 emissions as fossil fuel is burnt. To maintain the natural capital, the same amount that is emitted needs to be absorbed. The fact that more is emitted than is absorbed points to overshoot. More area could be dedicated to CO2 sequestration, and various carbon scheme, including REDD offer such approaches.

So not all necessary biocapacity may exist – and the result is overshoot (i.e., depletion). Van den Bergh and Grazi call this difference "hypothetical" – but in reality it is overshoot.

For every potato I eat I can calculate how many global hectares worth of biocapacity were occupied for a year to produce that potato. I may not know where exactly this area is, that offers this biocapacity, but it nevertheless exists somewhere on this planet.

If I use timber from a forest that was overharvested, the biocapacity demand is larger than what the forest contains. That forest is still real, but is being depleted – it is harvested more rapidly than timber regrows. Of course this is physically possible for some time, it is not hypothetical. The piece of timber came from a real forest. Overuse is not hypothetical, but leads to real depletion of the standing stock of that forest.

A field can be measured in both hectares (the geometric extension of the field), or in global hectares (the biocapacity it represents). Both measures reflect the physical nature of this field. Similarly, I can measure oil in weight, volume, or its energy content. All three are physical

description of this amount of oil. Few would label the various ways of measuring something physical "false concreteness".

12) CRITICISM: "Please separate the carbon Footprint from the remainder of the Footprint."

OUR RESPONSE: We offer all the accounting results in aggregate and also as its component. So if it makes more sense to report them separately, users can do this. However, the value of the Ecological Footprint accounts comes from their aggregation: to show the sum total of the human demand in comparison to the sum total of biocapacity.

There are clear trade-offs: we could dedicate more space to carbon sequestration, taking away space from agricultural surfaces. Ultimately, climate change is about biology: to what extent the biosphere is able to cope with the systematic accumulation of greenhouse gases in the atmosphere. The climate debate also recognizes that the atmosphere is coupled with the land, as explained in the IPCC report dedicated to land-use change (www.ipcc.ch/srccl).

Also, recognize that the carbon Footprint was about 0% of the total Ecological Footprint 200 years ago. To live up to the warming goal in the Paris Agreement, the carbon Footprint would have to be zero again well before 2050. However, moving out of fossil fuel might increase the pressure on other Footprint dimensions. For instance, more biomass may be employed to access the energy in the absence of fossil fuel. This means that in a decarbonization phase, changes in the carbon Footprint may be negatively correlated with the remaining Footprint. This underlines why the carbon Footprint cannot be seen as a proxy for the entire Footprint and looking at the whole is needed if we want to have a chance to build a future where all can thrive within the means of our planet.

13) CRITICISM: "Doesn't technological progress make resource accounting obsolete?"

OUR RESPONSE: Resource accounting is immensely relevant for anybody who recognizes that the economy depends on a physical planet.

Because of the dependence of all value chains on natural capital, some advocate for "**strong sustainability**", meaning that, in net-terms, no natural capital must be lost. For such a sustainability goal, harvest must be less than what is sustainably regenerated, and groundwater levels or biodiversity must not decline, etc.

Others advocate that as long as the loss of natural capital is compensated through other forms of capital formation, then the economy is still on a stable trajectory ("**weak sustainability**"). This is the technology argument: improvements that help an economy decrease its dependence

on natural capital allows it to operate on ever less natural capital. Nevertheless, even if one assumes that "weak sustainability" is sufficient, that economy would still need to monitor whether the natural capital is declining slower than the economy's dependence on this capital.

To succeed under a weak sustainability scheme, resource efficiency must outpace the loss of natural capital forever. If that succeeds, it is reasonable to assume that there would be no economic consequences as long as that economy reduces its physical dependence on natural capital faster than it depletes it. However, there could also be a diseconomy of scale, where maintaining economic activities becomes over-proportionally harder as available input becomes scarcer. In other words, the ratio between human demand and regeneration must not increase, year after year, otherwise weak sustainability falls apart. Therefore, weak sustainability also requires monitoring biocapacity and ecological footprints.

Yet, others may have the position that resource availability is not a relevant parameter for an economy; they may believe that there is no absolute dependence on the physical world. Therefore, they may refuse to monitor the resource situation of their economy. This is similar to a pilot refusing to have a fuel gauge on its cockpit dashboard. Yet, even if the pilot firmly believes that planes do not need to be refueled and therefore don't need a fuel gauge, planes will not fly forever.

14) CRITICISM: "Doesn't the drop in resource prices indicate that resource limitations are overplayed?" (from e-mail correspondence).

OUR RESPONSE: Ecological Footprint accounts do not make an economic argument per se. They just map human demand against regeneration. However, resource prices do not map resource use or resource regeneration. Prices have not reacted to the massive level of global ecological overshoot.

15) CRITICISM: "The Ecological Footprint is a great communication tool. But it is not policy relevant." (common criticism)

OUR RESPONSE: Ecological Footprint accounts measure how much biocapacity there is and how much is being used. The results seem to communicate well, including when translated into an Earth Overshoot Day date.

Whether these results are policy relevant needs to be determined by decision-makers. Our assumption is that regeneration (or biocapacity) is the materially most limiting factor, and that it is the competition for biocapacity that is the most useful lens in order to understand overall resource dependence. We also believe that physical reality does shape policy outcomes.

Whatever policy analysts assume, physical reality then decides whether the policy analysts' conclusions were realistic. One reason some analysts argue that the Ecological Footprint is not relevant to many current policy decisions may be rooted in the fact that many of these decisions are not sustainability relevant.

The more realistic our assumptions, the more likely our policy bets will turn out as we hoped.

Further Resources

More on the Ecological Footprint

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Web resources

- FootprintNetwork.org — offers, as Global Footprint Network's main site, all the background on the Ecological Footprint and its applications, linking back to its origins in the early 1990s when we coined the "footprint" term and developed its metric.

- www.FoDaFo.org is the home of the National Footprint and Biocapacity Accounts. Established in 2019, it is the organization jointly set up by York University in Toronto and Global Footprint Network to be the steward of the National Footprint and Biocapacity Accounts. It works directly with York University's Ecological Footprint Initiative for details see footprint.info.yorku.ca.

- Data.FootprintNetwork.org — provides all key results for the National Footprint and Biocapacity Accounts. This is the source of the widely used statistics on how many Earths we use.

- www.FootprintStandards.org provide guidance on how to produce consistent Ecological Footprint applications at all scale, including assuring consistency with results from the National Footprint and Biocapacity Accounts.

- FootprintCalculator.org — allows individuals to estimate their own Footprint and their personal Overshoot Date. We have 3 million annual users, up from 2 million in 2017, with plans to reach 10 million per year within two years. This is the primary entry point to the #MoveTheDate map.

- OvershootDay.org — hosts Earth Overshoot Day and features solutions to #MoveTheDate (reached 2 billion media-impressions in 2017, 3 billion in 2018, and 4 billion in 2019, with ambition to reach 10 billion within 3 years).

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