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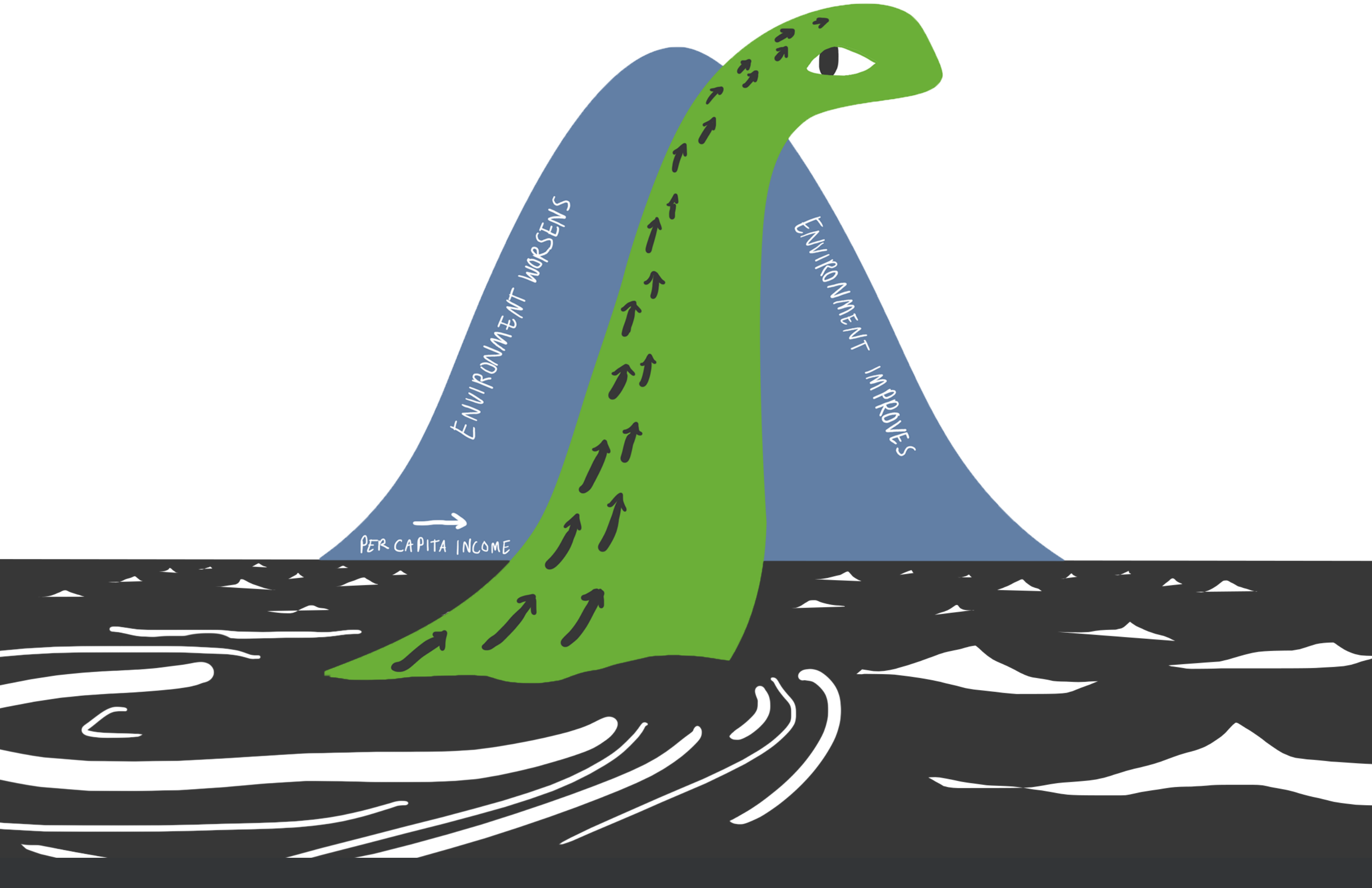
Decoupling Debunked

Evidence and arguments against green growth as a sole strategy for sustainability



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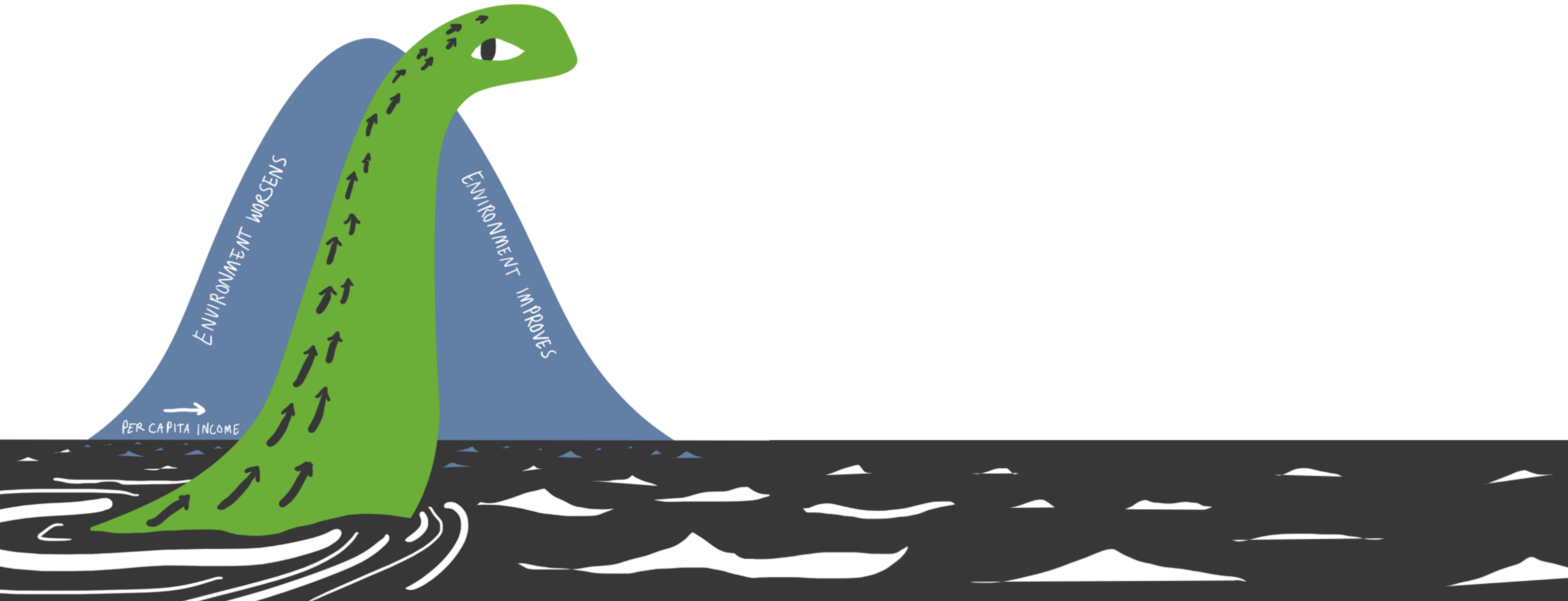
Corresponding author at: tparrique@gmail.com

July 2019



Date of publication

July 2019

Authors of the report

Timothée Parrique, Centre for Studies and Research in International Development (CERDI), University of Clermont Auvergne, France; Stockholm Resilience Centre (SRC), Stockholm University, Sweden

Jonathan Barth, ZOE.Institute for Future-Fit Economies, Bonn, Germany

François Briens, Independent, Informal Research Centre for Human Emancipation (IRCHE)

Christian Kerschner, Department of Sustainability, Governance, and Methods, MODUL University Vienna, Austria; Department of Environmental Studies, Masaryk University, Brno, Czech Republic

Alejo Kraus-Polk, University of California, Davis, USA

Anna Kuokkanen, Lappeenranta-Lahti University of Technology, Lahti, Finland

Joachim H. Spangenberg, Sustainable Europe Research Institute (SERI Germany), Cologne, Germany

The full report should be referenced as follows

Parrique T., Barth J., Briens F., C. Kerschner, Kraus-Polk A., Kuokkanen A., Spangenberg J.H., 2019.

Decoupling debunked: Evidence and arguments against green growth as a sole strategy for sustainability.

European Environmental Bureau.

Corresponding author tparrique@gmail.com

Report available online at eeb.org/decoupling-debunked

Report produced for and disseminated by

The European Environmental Bureau
www.eeb.org

With the assistance of

Deutscher Naturschutzring
www.dnr.de

With research support from

Zoe. Institute for Future-Fit Economies
zoe-institut.de/en

Acknowledgements

We would like to thank everyone who has contributed to this report in various ways: Sam Bliss, Maria Brück, Martin Bruckner, Iñigo Capellán Pérez, Mikuláš Černík, Fabrice Flipo, David Font, Jaune Freire, Mario Giampetro, Stefan Giljum, Christoph Gran, Klaus Hubacek, Theresa Klostermeyer, Anna-Lena Laurich, Nick Meynen, Patrizia Heidegger, Katharina Wiese, Simon de Muynck, and Hannah Strobel. Special thanks to Kristin Langen for initiating the project.

The responsibility for errors remains with the authors.

Lay-out and printing: Cooperative eco-printery De Wrikker cvba - www.dewrikker.be

Illustrations: Gemma Bowcock (EEB)

Executive summary

Is it possible to enjoy both economic growth and environmental sustainability? This question is a matter of fierce political debate between green growth and post-growth advocates. Over the past decade, green growth clearly dominated policy-making with policy agendas at the United Nations, European Union, and in numerous countries building on the assumption that decoupling environmental pressures from gross domestic product (GDP) could allow future economic growth without end.

Considering what is at stake, a careful assessment to determine whether the scientific foundations behind this "decoupling hypothesis" are robust or not is needed. This report reviews the empirical and theoretical literature to assess the validity of this hypothesis. The conclusion is both overwhelmingly clear and sobering: not only is there no empirical evidence supporting the existence of a decoupling of economic growth from environmental pressures on anywhere near the scale needed to deal with environmental breakdown, but also, and perhaps more importantly, such decoupling appears unlikely to happen in the future.

It is urgent to chart the consequences of these findings in terms of policy-making and prudently move away from the continuous pursuit of economic growth in high-consumption countries. More precisely, existing policy strategies aiming to increase efficiency have to be complemented by the pursuit of sufficiency, that is the direct downscaling of economic production in many sectors and parallel reduction of consumption that together will enable the good life within the planet's ecological limits. In the view of the authors of this report and based on the best available scientific evidence, only such strategies respect the EU's 'precautionary principle', the principle that when the stakes are high and the outcomes uncertain, one should err on the side of caution.

The fact that decoupling on its own, i.e. without addressing the issue of economic growth, has not been and will not be sufficient to reduce environmental pressures to the required extent is not a reason to oppose decoupling (in the literal sense of separating the environmental pressures curve from the GDP curve) or the measures that achieve decoupling - on the contrary, without many such measures the situation would be far worse. It is a reason to have major concerns about the predominant focus of policymakers on green growth, this focus being based on the flawed assumption that sufficient decoupling can be achieved through increased efficiency without limiting economic production and consumption.

Main findings

> Discussing decoupling requires using a rigorous analytical framework. Depending on the indicators considered to account for economic activities and environmental pressures as well as the range of their evolution, decoupling can be characterised in different ways. It can be global or local, relative or absolute, territorial- or footprint-based, happen over a short or a long period of time, and last but not least, it should be put in perspective with relevant environmental thresholds, political targets and the global socio-economic context, as to assess its adequacy in magnitude taking into account equity considerations.

> The validity of the green growth discourse relies on the assumption of an absolute, permanent, global, large and fast enough decoupling of economic growth from all critical environmental pressures. The literature reviewed clearly shows that **there is no empirical evidence for such a decoupling currently happening**. This is the case for materials, energy, water, greenhouse gases, land, water pollutants, and biodiversity loss for which decoupling is either only relative, and/or observed only temporarily, and/or only locally. In most cases, decoupling is relative. When absolute decoupling occurs, it is observed only during rather short periods of time, concerning only certain resources or forms of impact, for specific locations, and with very small rates of mitigation.

> There are at least **seven reasons to be sceptical** about the occurrence of sufficient decoupling in the future. Each of them taken individually casts doubt on the possibility for sufficient decoupling and, thus, the feasibility of "green growth." Considered all together, **the hypothesis that decoupling will allow economic growth to continue without a rise in environmental pressures appears highly compromised, if not clearly unrealistic**.

1 **Rising energy expenditures**. When extracting a resource, cheaper options are generally used first, the extraction of remaining stocks then becoming a more resource- and energy-intensive process resulting in an increase in total environmental degradation per unit of resource extracted.

2 **Rebound effects**. Efficiency improvements are often partly or totally compensated by a reallocation of saved resources and money to either more of the same consumption (e.g. using a fuel-efficient car more often), or other impactful consumptions (e.g. buying plane tickets for remote holidays with the money saved from fuel economies). It can also generate structural changes in the economy that induce higher consumption (e.g. more fuel-efficient cars reinforce a car-based transport system at the expense of greener alternatives, such as public transport and cycling).

3 **Problem shifting**. Technological solutions to one environmental problem can create new ones and/or exacerbate others. For example, the production of private electric vehicles puts pressure on lithium, copper, and cobalt resources; the production of biofuel raises concerns about land use; while nuclear power generation produces nuclear risks and logistic concerns regarding nuclear waste disposal.

4 **The underestimated impact of services**. The service economy can only exist on top of the material economy, not instead of it. Services have a significant footprint that often adds to, rather than substitute, that of goods.

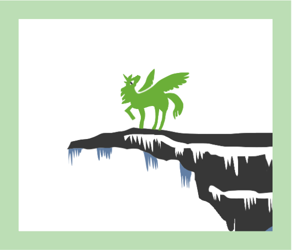
5 **Limited potential of recycling**. Recycling rates are currently low and only slowly increasing, and recycling processes generally still require a significant amount of energy and virgin raw materials. Most importantly, recycling is strictly limited in its ability to provide resources for an expanding material economy.

6 **Insufficient and inappropriate technological change**. Technological progress is not targeting the factors of production that matter for ecological sustainability and not leading to the type of innovations that reduce environmental pressures; it is not disruptive enough as it fails to displace other undesirable technologies; and it is not in itself fast enough to enable a sufficient decoupling.

7 **Cost shifting**. What has been observed and termed as decoupling in some local cases was generally only apparent decoupling resulting mostly from an externalisation of environmental impact from high-consumption to low-consumption countries enabled by international trade. Accounting on a footprint basis reveals a much less optimistic picture and casts further doubt on the possibility of a consistent decoupling in the future.

\> This report highlights the need for a new conceptual toolbox to inform and support the design and evaluation of environmental policies. Policy-makers have to acknowledge the fact that addressing environmental breakdown may require a **direct downscaling of economic production and consumption** in the wealthiest countries. In other words, we advocate complementing efficiency-oriented policies **with sufficiency policies**, with a shift in priority and emphasis from the former to the latter even though both have a role to play. From this perspective, it appears urgent for policy-makers to pay more attention to and support the developing diversity of **alternatives to green growth**.

Contents



Introduction

Is economic growth compatible with ecological sustainability? Almost half a century after the publication of the Meadows report "Limits to growth" and Sicco Mansholt's letter to the President of the European Commission in 1972 in defence of a shift away from the pursuit of economic growth, the relation between Gross Domestic Product (GDP) and environmental pressures remains a matter of fierce political debate.

The debate has two main sides. Proponents of what has been named "green growth" argue that technological progress and structural change will enable a decoupling of natural resources consumption and environmental impacts from economic growth. On the other hand, advocates of "degrowth" or "post-growth" argue that, because an infinite expansion of the economy is fundamentally at odds with a finite biosphere, the reduction of environmental pressures requires a downscaling of production and consumption in wealthiest countries, which is likely to result in a decrease in GDP compared to current levels. On one side, green growth advocates expect *efficiency* to enable more goods and services at a lower environmental cost; on the other, degrowth proponents appeal to *sufficiency*, arguing that less goods and services is the surest road to ecological sustainability.

Today, the green growth narrative dominates most political circles. In 2001, the Organisation for Economic Co-operation and Development (OECD) officially adopted decoupling as a goal, which later came to play a key role in its strategy *Towards Green Growth* (2011).[1] It was then followed by the European Commission who, in its 6th Environment Action Programme (*Environment 2010: Our Future, Our Choice*), announced its objective to "break the old link between economic growth and environmental damage" (EU Commission, 2001, p. 3). The commitment of "decoupling growth from resource use" was repeated in the EU Roadmap to a Resource-Efficient Europe (European Commission, 2011), and in the United Nations Environment Programme (UNEP)'s strategy on green economy (2011a, p. 18) where green growth was expected to "significantly reduce environmental risks and ecological scarcities."[2,3]

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[1] Which they defined as the "breaking of the link between 'environmental bads' and 'economic goods' " (OECD, 2002, p. 1).

[2] "A key concept for framing the challenges we face in making the transition to a more resource-efficient economy is decoupling. As global economic growth bumps into planetary boundaries, decoupling the creation of economic value from natural resource use and environmental impacts becomes more urgent" (UNEP, 2011b, pp. 15–16, italics added).

[3] "Target 8.4: Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-Year Framework of Programmes on Sustainable Consumption and Production, with developed countries taking the lead".

Soon after, the World Bank joined the bandwagon with *Inclusive Green Growth: The Pathway to Sustainable Development* (2012).[4] Since 2012, the 7th Environmental Action Programme guiding the European Commission's environmental policy until 2020 *Living well, within the limits of our planet* (European Commission, 2013) calls for "an absolute decoupling of economic growth and environmental degradation." And in 2015, decoupling became a specific target in the Sustainable Development Goals (SDGs).

Green growth has dominated the discussion and set most of the environmental agenda based upon the expectation of a decoupling of economic growth and environmental pressures. A situation with such high stakes calls for a careful assessment to determine whether the scientific foundations behind the decoupling hypothesis are robust or not. This is the subject of this report, and as its title clearly indicates, we have found insufficient theoretical and empirical support to warrant the hopes currently placed in decoupling.

The literature on decoupling is abundant. Starting in 2011, UNEP has produced a series of reports on the topic (UNEP, 2011b, 2014a, 2015). Searching the keywords "decoupling economic growth" on Scopus delivers more than 600 articles, most of them empirical. On such a controversial topic, one would expect wide divergence in results. Yet, as we will show in the second section of this report, disagreements within that literature mainly result from slight variations in the way decoupling is defined and measured. Once these methodological quirks are set aside, findings converge towards showing that there is no robust evidence justifying the idea of decoupling as a single or main policy strategy as it is currently promoted by green growth advocates.

This report is organised in three sections. First, we define what decoupling means and specify the different forms that it can take. The main point of this section is that behind one term hides various different meanings or situations, some of them more desirable than others. In the second section, we review the empirical literature on the topic as to assess whether or not there is evidence of decoupling having occurred in the past. Our finding is that current scientific knowledge does not support the hypothesis of the type of decoupling that would be necessary to effectively address climate change and other environmental crises. In the third section, we discuss how likely is decoupling to occur in the future and find that probabilities are too thin to warrant the current central focus placed on the concept in policy making. In conclusion, the main claim of the report is that green growth, that is economic growth that is sufficiently decoupled from environmental pressures, is not possible and should thus not be the primary objective of environmental policy.

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[4] For the World Bank (2012) inclusive green growth is "economic growth that is efficient in its use of natural resources, clean in that it minimizes pollution and environmental impacts, and resilient in that it accounts for natural hazards and the role of environmental management and natural capital in preventing physical disasters."

I. What is decoupling?

A constructive discussion requires starting with explicit definitions and clarifying several terminological and methodological subtleties, having to do with what type of economic and environmental indicators are considered and how they are statistically correlated; at which scale, magnitude, and timing decoupling may or may not occur; as well as for what outcomes in terms of achieving social and environmental targets.

1. Relative and absolute decoupling

Generally speaking, two variables are said coupled if one is driven by the other, making them evolve in proportion (for instance, more of A means more of B); and they decouple when they cease to do so. When coupled, both the driven and driving variables move in step, which means that they evolve over time proportionally. Decoupling refers to a variation over time of the coefficient of proportionality, corresponding to a desynchronization between the two variables tends.

This decoupling can be either *relative* or *absolute* (also called *weak* or *strong*). *Relative decoupling* means that both variables still develop into the same direction but not at the same speed (a lot of more of A means a little more of B) whereas absolute decoupling means that the two variables go in opposite directions (more of A and less of B). Assessing decoupling means estimating the loss of proportionality between one variable towards another (or more precisely the variable trends) over time.

Relative decoupling, for example between GDP and carbon emissions, refers to a situation where the emissions per unit of economic output (the coefficient of proportionality) declines but not “fast enough” to compensate for the simultaneous increase in output over the same period, resulting in an overall increase in total emissions. As a result, although the economy is relatively less impactful per unit of GDP compared to what it was before, the absolute volume of emissions has nonetheless increased.

Absolute decoupling is a situation where, to stay with the same example, more GDP coincides with lower emissions. Relative decoupling becomes *absolute* decoupling when the growth rate of the economy is overcompensated by the growth rate of efficiency or productivity having to do with the use of natural resources and the generation of pollutions – a threshold sometimes referred to as the “absolute decoupling point” (Akizu-Gardoki et al., 2018). When decoupling is absolute, environmental pressures decline without a corresponding drop in economic activities, or vice versa, economic activities rise without an increase in environmental pressures.

2. The driving variable: Gross Domestic Product

In the decoupling of economic growth from environmental pressures, the first term refers to a measure of market activity, most often Gross Domestic Product (GDP).[5] GDP is a measure of the aggregate market value of all the final goods and services produced in a country in a given period (often annually), and it is the change of that value that is called economic growth. Calculating GDP is an intricate process resulting from a number of conventions and involving a number of subtleties having to do with what to include and exclude and how to measure it. Since its creation in the 1930s, GDP has been criticised on many grounds. Although this is not the space to review such criticisms, one should still say that the primacy of this indicator reflects a narrow, potentially problematic, framing of prosperity. This being said, in our context, it matters to take into consideration GDP evolutions in volume or “real GDP,” that is to say to correct GDP from inflation.

3. The driven variable: Resources and impacts

Environmental pressures include all the consequences an economy has on nature. Following UNEP (2011b), it is possible to distinguish between *resource use* and *environmental impacts*. *Resource* decoupling is a decoupling of market activity from the volume of resource used (i.e. extracted from the environment), for example, thanks to efficiency improvements or better recycling which both allow for less extraction. It means that the same or a larger output in monetary terms can be produced with fewer material inputs. The term “resource” here refers to “natural assets deliberately extracted and modified by human activity for their utility to create economic value” (UNEP, 2011b, p. 2).[6] In this report, we will divide the natural resources used for economic activities in four categories: *materials*,[7] *energy*, *water*, and *land* (the latter two defined broadly as to include biodiversity and related ecosystem services). These resources can be measured using different indicators either production-based (e.g. domestic extraction, primary energy supply, land occupation) or consumption-based (e.g. material footprint, energy footprint, water footprint, or ecological footprint).

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[5] There exist other ways of quantifying economic activity, such as total working time or aggregate employment. A small minority of decoupling studies focus on more encompassing indicators such as the Human Development Index (Akizu-Gardoki et al., 2018); the Index of Sustainable Economic Welfare (Beça and Santos, 2014); need satisfiers and human well-being (O’Neill et al., 2018). In the report, however, we only focus on economic growth measured as an increase in GDP for that it is measured as such in the great majority of decoupling studies.

[6] The way one accounts for resources matters. For example, including unused extraction of materials (the materials and energy being used, displaced, or damaged in the process of extraction itself) often leads to calculated volumes a few order of magnitude higher than only counting the inputs to the production process itself. In the case of Chile, for example, the physical trade balance in the year 2003 increases from net exports of 1 million tons in terms of direct flows to net exports of 634 million tons if calculated including unused extraction materials (Muñoz et al., 2009).

[7] Materials can be further broken down into more detailed categories such as, for example, biomass, fossil energy carriers, ores and industrial minerals, and construction minerals (Fischer-Kowalski et al., 2011, p.10)

Impact decoupling refers to a decoupling of GDP from environmental impacts, that is a decrease in environmental harm per unit of economic output. Environmental impacts can take various forms such as waste disturbing marine life or pollutants affecting human and animal health, disturbance of natural processes (e.g. nitrogen, phosphorus, carbon, and fresh water cycles) or biodiversity loss. There is usually a link between resource use and environmental impacts; for example, extracting and using more fossil fuels (*resource*) generates CO_2 emissions contributing to climate change (*impact*). Although most empirical studies focus on climate change and greenhouse gas emissions, any deleterious effects on the biosphere can be taken into consideration as an environmental variable (e.g. light pollution leading to biodiversity loss, water pollution leading to eutrophication).

In this report, we will refer to *overall* decoupling for cases where decoupling occurs between GDP and all selected indicators, including both resource use and environmental impacts. And we will refer to *partial* decoupling for cases where one or more environmental indicators decouple from GDP while coupling remains or intensifies for other indicators.

4. Scale: Global or local

Decoupling can be discussed taking into consideration different geographical perimeters. *Local* decoupling refers to cases where decoupling is observed between variables relative to a restricted geographical perimeter (e.g. a country or a water basin), while *global* decoupling corresponds to decoupling between two variables at the planetary scale (e.g. world GDP and world greenhouse gas emissions).[8]

The relevance of using local or global indicators depends on the nature of the environmental pressure considered and on its causes. For instance, to study local issues, such as the eutrophication of the Baltic Sea, for which direct causes are located in a rather well defined geographic area, it makes sense to use local indicators, limited, for example, to the perimeter of the watershed. However, global issues like climate change generally call for global indicators, since greenhouse gases are transboundary pollutants and climate change is a planetary phenomenon.

In a globalised world, the choice of the boundaries considered for the system under study matters. Globalisation and the expansion of international trade has led to a spatial dissociation between places of extraction, production, and consumption, making it more difficult to determine who is responsible for which impacts. In this context, *production-based* (also called *territorial*) indicators, which relate to geographical areas rather than to populations, cannot reflect responsibilities and are as such insufficient. A more comprehensive approach consists in looking at *consumption-based* (also called *footprint*) indicators, in which embodied impacts from production and end-of-life phases of traded goods and services are geographically reallocated to final consumers. Indeed, not accounting for the resources mobilised and for impacts generated abroad may lead to detecting apparent decoupling at a local level for importing countries which translocate impacting activities abroad. Reversely, territorial

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[8] One could even go further and differentiate several local levels: macroeconomic (for instance taking into account the whole national activity), sectoral (a specific sector of the economy), and microeconomic (single company, city, household). In this report this will not be necessary for that the majority of empirical studies are either national, regional, or global.

approaches might underestimate decoupling in the case of exporting countries who host impacting activities intended for the consumption of other nations.

5. Durability: Temporary or permanent

Just like the geographical perimeter, the time period of a decoupling study matters. Indeed, mitigating environmental pressures in a growing economy not only implies achieving absolute decoupling from GDP, but also requires maintaining such a decoupling in time *as long as the economy grows*. Said differently, continuous economic growth requires a *permanent* absolute decoupling between GDP and environmental pressures. Yet, in the same way that economic growth and environmental pressures can *de*couple at one point in time, they can also *re*couple later on. As empirical studies often show, decoupling can as well be temporary, resulting in a further increase of environmental pressures after a temporary relief. In the literature, this situation is depicted by an N-shaped curve and sometimes referred to as *recoupling* or “relinking” (de Bruyn and Opschoor, 1997; Jänicke et al., 1989)indicating a ‘delinking’ of environmental pressures from economic growth in relation to rising per capita incomes. The likelihood of such a relationship being persistent is discussed in the context of a simple macro model of industrial metabolism, and the possibility of ‘relinking’ clearly emerges. Data on specific indicators of environmental pressures (i.e. the throughput of materials, energy and the volume of transport.

Such pattern can, for instance, result from a large shift in energy sources. For example, China moving from coal toward oil and gas and the US increasing the portion of natural gas in their energy mix caused a temporary levelling of global emissions in 2015 and 2016 reported by the International Energy Agency (IEA). But this decoupling was short-lived: once the shift was completed and the corresponding decoupling potential spent, emissions recoupled with economic growth (+1.6% in 2017 and +2.7% in 2018) (Hickel and Kallis, 2019, p.8). Another common example of temporary decoupling is the Global Financial Crisis of 2007-2008 which, as we will see in detail in Section 2, has momentarily pushed environmental pressures down.

From an ecological sustainability perspective, the necessary type of decoupling is one that is *permanent* and not only *temporary*. Indeed, it makes little sense to cut resource use or emissions drastically in the short-term only to fall back on a path of increased biophysical intensity in the longer term. Besides, temporary decoupling only has a marginal effect on environmental pressures resulting from cumulative impacts, an effect which merely boils down to a time lag. Findings from decoupling studies should therefore be put in perspective with the time period considered for what may look like decoupling over a short period (inverted U-shape curve) might look different over a longer period (N-shape curve).

6. Magnitude: Sufficient or insufficient

A 3% rise in GDP with a 2% drop in total greenhouse gas emissions is by definition absolute decoupling, but so is a 3% rise in GDP with a 0.02% drop in emissions. Plain to see that the first is more desirable if the goal is to mitigate climate change. Our point is the following: the success of a decoupling strategy should be assessed in relation to specific environmental targets, and not in terms of abstract decoupling elasticities as often done in the literature. Once such targets have been defined, one can then speak of decoupling being *insufficient* or *sufficient* in achieving them – e.g. “absolute decoupling within planetary boundaries” for Fedrigo-Fazio et al. (2016).

Furthermore, talking about emission or resource productivity measured in emissions/resource per unit of GDP obscures the fact that most environmental issues are caused by cumulative, absolute impacts from different factors. In reality, not only does this imply that to be effective, the required decoupling would have to be covering both resource use and impacts, in both dimensions being *absolute*, *global*, and *permanent*, but it would also need to be *sufficiently fast*. Long before being exhausted, non-renewable resources get scarce and can create conflicts or exacerbate already existing ones. Adaptation is even more difficult in the case of ecosystem overload; once overwhelmed – i.e. if *tipping points* have been passed – they can collapse or transform into a different kind of system (e.g. a forest area becoming savannah). Both kinds of damage – exhaustion and collapse – are often irreversible on a time-scale relevant for humans. Even though it is difficult to measure, decoupling can be considered *sufficiently fast* if the absolute decoupling point is reached before passing irreversible thresholds of damage such as the nine planetary boundaries identified by Rockström et al. (2009), Steffen et al. (2015) and Steffen et al. (2018).[9]

Climate change provides a good example of a hard deadline for absolute impact decoupling. With a global carbon budget estimated at 580 $GtCO_2$ that is currently being depleted at the pace of 42 $GtCO_2$ per year, this leaves less than 15 years at current rates of emissions. Reaching the net zero anthropogenic CO_2 by 2040 necessary to limit global warming to 1.5°, which a high level of confidence requires an annual reduction of at least 5% of the current emissions. Following this trajectory, the budget will last 20 years and the emissions will be zero at the end of the period – with 45% decline in global emissions by 2030 as an interim target (IPCC, 2018). In light of this constraint, and as we will show in Section 2, even the decrease of emissions achieved in the most successful national cases of absolute decoupling are far from being sufficient to keep global warming from passing a critical threshold.

Urgency does not only concern impacts but also resources. The preservation of non-renewable resources is a matter of intra- and intergenerational equity. Each non-renewable resource used in one place is a resource that will not be available in another place, and each non-recyclable resource used today is a resource that will not be available tomorrow. As for renewable ones, the threshold of sustainable consumption is set by the replenishment rates of that resource (e.g. avoiding a fish stock being depleted to extinction or the collapse of soil structure). So when UNEP (2014a, p. 123) concludes their report by affirming that “absolute decoupling of economic growth from resource use is possible,” we want to point out that it is the magnitude and timing of that decoupling which is at stake more than its mere statistical existence.

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[9] To be precise, one should say that the environmental pressures occurring after the decoupling point, even though decreasing, still matters. Enough resources or carbon budgets (or any other measure of resource and impacts) should be left as to be able to afford the descent from the peak with still remaining within thresholds of ecosystem stability.

7. Equity in the allocation of decoupling efforts

The last dimension comes on top of the previous one and is about the concept of “shared but differentiated responsibilities” that ever since first agreed at the 1992 United Nations Conference on Environment and Development (UNCED) in Rio figures in climate agreements. Decoupling needs to be sufficiently *large* in affluent countries in order to free the ecological space necessary for production and consumption in regions where basic needs are unmet.

The fact that there are millions of people in the world who lack access to the means of satisfying their basic needs puts extra pressures on rich nations to reduce environmental pressures *as much as possible* as to give the largest possible leeway to vulnerable communities. If moving the “global poor” to an income level of US$ 3-8 per day will by itself consume 66% of the available 2°C global carbon budget (Hubacek et al., 2017), then it is imperative for affluent nations to let go of the remaining available climate space. Meyer-Ohlendorf et al. (2018) calculate that, if the share of carbon budget is derived from 2050 population numbers as to better account for equity, the current EU target for 2030 would have to almost double, from 40% reduction of emissions to 71%. Indeed, even if the metabolic rates of industrial countries would remain stable at 2000 levels (which would already imply absolute decoupling), the catching up of the rest of the world, using current technology, would in itself quadruple global emissions by 2050 (Fischer-Kowalski et al., 2011, p29), which corresponds to levels considered catastrophic in the latest Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 2018).

And again, in a world of limited resources, the timing of the peak impact matters as the “safe operating space” (Steffen et al., 2015) may not be large enough for every nation to peak in a logic of “grow now, clean up later” (Van Alstine and Neumayer, 2010, p. 57). For example, Storm and Schröder (2018, pp. 20–21) estimate that if China develops along the path of the production-based Environmental Kuznets Curve (EKC) they find for CO_2 emissions, they would exhaust the entirety of the world carbon budget before even reaching the hypothetical turning point. Decoupling in rich countries can be considered *large enough* if it compensates for the increased ecological footprint of poorer nations while still managing to absolutely and permanently decouple global economic growth from environmental pressures at a pace that is fast enough to avoid overshooting safe environmental thresholds.[10]

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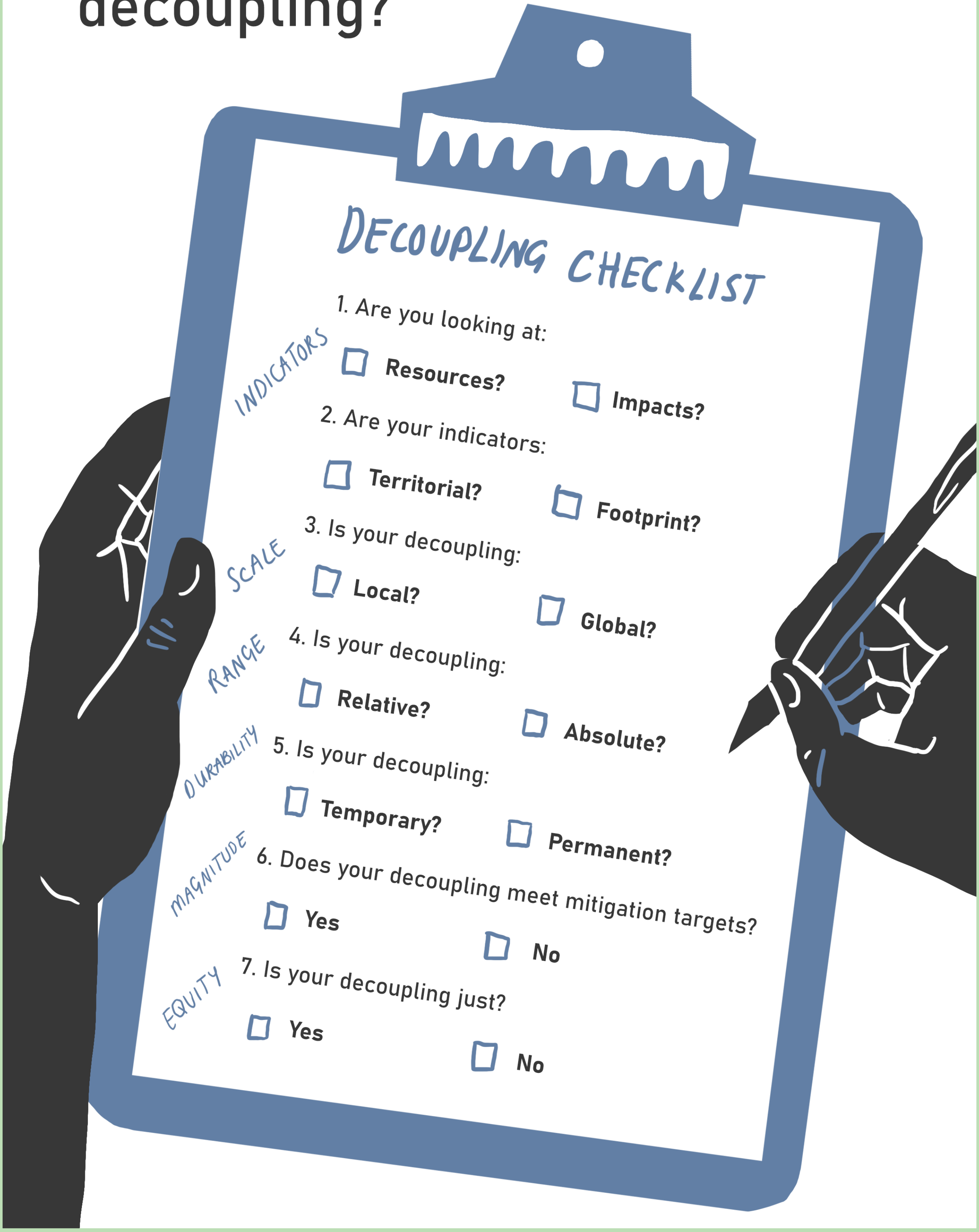
[10] This is a moral, and not a technical, question. Our main point here is that an abstract objective of decoupling is senseless if not connected to concrete environmental targets, which should themselves be based on moral considerations.

How are you measuring your decoupling?



DECOUPLING CHECKLIST

1. Are you looking at:

☐ **Resources?** ☐ **Impacts?**

2. Are your indicators:

☐ **Territorial?** ☐ **Footprint?**

3. Is your decoupling:

☐ **Local?** ☐ **Global?**

4. Is your decoupling:

☐ **Relative?** ☐ **Absolute?**

5. Is your decoupling:

☐ **Temporary?** ☐ **Permanent?**

6. Does your decoupling meet mitigation targets?

☐ **Yes** ☐ **No**

7. Is your decoupling just?

☐ **Yes** ☐ **No**

Conclusions for Section 1

As we have shown in this section, decoupling can be defined and measured in different ways. Consequently, carrying a literature review on decoupling calls for a number of precautions. First, one should be clear about *what* is being decoupled from *what*, specifying the indicators chosen to account for economic activities and environmental pressures. In particular, one should consider whether these indicators are global or local and whether they reflect territorial (production-based) or footprint (consumption-based) approaches (*scale*). Then it matters whether decoupling is studied and discussed in relative or absolute terms, and over a short or long period of time (*durability*). Last but not least, any observed decoupling should be put in perspective with relevant environmental thresholds and within a broader political context as to assess whether it manages to reach mitigation targets (*magnitude*) in a way that is deemed just (*equity*). Building on this analytical framework, the next section proposes a review of existing empirical literature on decoupling.

II. Is decoupling happening?

Is decoupling occurring in reality, and if yes, what kind of decoupling is it? The objective of this section is to assess the validity of the decoupling hypothesis in light of existing empirical research. To do so, we conduct a comprehensive literature review of a number of empirical studies having tested the decoupling hypothesis. The discussion that follows is organised thematically, according to the environmental variables considered: (1) *resources* (materials, energy, and water) and (2) *impacts* (greenhouse gases, land, water pollutants, and biodiversity loss). In each case, we compare the results reported across studies assessing them with respect to the different dimensions presented in Section 1.

Before diving into the empirical literature, it is worth telling the story of how scientists came to talk of decoupling in the first place. In the 1990s, several economists (Grossman and Krueger, 1995, 1991; Panayotou, 1993; Shafik and Bandyopadhyay, 1992) conducted empirical work that led them to believe that economic growth was negatively correlated with environmental pressures.[11] Environmental impacts would first grow but then decline in an inverted bell shaped development that came to be referred to as an *Environmental Kuznets Curve*.[12] This theory had strong policy implications as it meant that a nation could grow its way out of an ecological crisis.

This hypothesis of what UNEP (2014a, p. 5) calls a “decoupling through maturation” has inspired a number of studies in the following decades looking for EKCs for a selection of environment variables. Today, such assumption of a naturally-occurring decoupling has lost traction in both scientific and political scenes while it has been recognised that the structural change of economies leading to decoupling is strongly determined by policies (Smith et al., 2010; UNEP, 2014a). The way to study

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[11] Grossman and Krueger (1991)studied air pollutants (sulphur dioxide and other particulates); Shafik and Bandyopadhyay (1992) focused on water pollution, municipal waste, particulates, sulphur dioxide, deforestation, and carbon emissions; and Panayotou (1993) considered an array of similar environmental indicators.

[12] In 1955, Simon Kuznets elaborated the theory that in the process of expanding economic activity, inequality first increased to a maximum and then decreased – thus forming an inverted U-shaped curve.

decoupling has thus evolved from a semi-natural phenomenon to something that can be brought into existence via policy intervention.

In this perspective, we will present a review of recent empirical studies that attempted to identify decoupling phenomena, adding to existing literature reviews like Li et al. (2007), Koirala et al. (2011) or Mardani et al. (2019). Although the literature review we conduct is one of the most encompassing up to date, it is not systematic and exhaustive, and so the claims we make about the decoupling literature should be appreciated in regards to the limited pool of articles under consideration (see the full list in the appendix). It is also worth noting that the majority of studies have to do with developed countries (with notable exceptions, e.g. Wang et al., 2019), and so the claim we make about decoupling should be understood in that context.[13]

1. Resource decoupling

Materials

When it comes to aggregate use of materials, the evidence is clear and uncontroversial. There has been no absolute decoupling of resource use from economic growth. In fact, the global use of resources is on the rise and global GDP is still tightly coupled with total resource extraction. Here and in the rest of this section, if not otherwise indicated, the decoupling effects are estimated on the basis of production-based environmental variables.

Global material extraction has increased by a factor of 12 in between 1900 and 2015, with a steady acceleration since the beginning of the 21st century (Krausmann et al., 2018).[14] In the last century, average resource use per capita doubled: a global inhabitant in 2005 required somewhere between 8.5 (Behrens et al., 2007) and 9.2 tons (Krausmann et al., 2009) of resources annually, while a hundred years earlier this number was only 4.6 tons (UNEP, 2011b, p. 10).[15] Only in the last 40 years, total material use at the global level has tripled (Schandl et al., 2018). The material footprint of the OECD nations as a whole increased by almost 50% between 1990 and 2008 in direct relationship with economic activity with every 10% rise in GDP being accompanied with a 6% increase in material footprint (Wiedmann et al., 2015).[16] In the end, the material intensity of GDP per capita has increased by 60% between 1900 and 2009 (Bithas and Kalimeris, 2018).[17]

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[13] This is not to say that decoupling is easier in the global South. Nor do we mean that the questions at hand in this report are solely a concern for the global North; ecological sustainability should be a matter of concern for all. However, we assume that if the global North fails to decouple, it will be hard to justify why decoupling should be expected to happen in low-income and technologically less advanced countries.

[14] Global material extraction increased by 53% between 2002 and 2015, which means that "roughly one third of all materials that have been extracted since 1900 have been mobilized between 2002 and 2015 only" (Krausmann et al., 2018, p.139).

[15] Schandl et al. (2018, p.4) notes that most of this increase is recent. Indeed, average global material extraction has risen from 7 tones per capita in 1970 to 10 in 2010.

[16] Bithas and Kalimeris (2018) confirm this dependency of the global economy on natural resources. They calculate that the global per capita consumption of mass resources increased by 78.7% over the last century (1900-2002); this means that a 4.8-fold increase in global income led to a 8.5-fold rise in mass flow. Considering biomass, fossil energy carriers, ores and industrial minerals, and construction minerals, Krausmann et al. (2018) calculate that global material use increased by a factor of 12 over the 1900-2015 period with a marked shift from the dominance of renewable biomass towards mineral materials.

[17] Same result for Giljum et al. (2014): 93.4% increase in global consumption between 1980 and 2009, which becomes 132% when extended to the year 2013 ("The Material Flow Analysis Portal," 2015). Again, that rate picks up at the turn of the century: around 2.5% average increase per year over the period but 3.4% rise between 2000 and 2009 (Giljum et al., 2014) or 3.85% between 2002 and 2013 (Materialflows.net, 2015).

Global material footprint targets are less consensual than carbon targets, and yet an emerging consensus holds that material consumption needs to be capped to a yearly maximum of 50 billion tons in order to remain ecologically sustainable (Bringezu, 2015; Dittrich et al., 2012; Hoekstra and Wiedmann, 2014; UNEP, 2014b). In 2009, that number was already over the threshold at 67.6 billion tons (Giljum et al., 2014).

A surprising fact shown in all studies is that while the world economy had been gradually dematerialising for a long time, this trend has been reversed in the last two decades. While in the last century the use of materials was *relatively* decoupling from GDP at the global level, the trend has stalled and reverted since the turn of the century. For instance, Krausmann et al. (2018) show that change in material intensity went from a negative 0.9% per year between 1945-2002 to a positive yearly 0.4% between 2002 and 2015. Attempting the same calculation with a different method, Bithas and Kalimeris (2018) find total decreases of material intensity in the range of 31.9% for 1900-1945 and 48.9% for 1950-2000, but only a decrease of 0.6% in between 2000 and 2009. Giljum et al. (2014) call it a *re-materialisation*, which is the opposite of decoupling, namely an increase in the material intensity of the world economy.

From the onset, it seems that rich countries achieve a faster relative decoupling than others. Yet, this performance wafts away when accounting for cost shifting, i.e. looking at consumption-based accounts. For example, Wang et al. (2018) compare consumption-based (material footprint) and production-based measurements (domestic material consumption) of resource use for the case of six countries, three from the OECD and three from emerging national economies: Brazil, Russia, India, China and South Africa (BRICS). Australia, Japan, India, and the US do manage to relatively decouple, but only because they shift their material resource supply abroad. This result is confirmed by both Bithas and Kalimeris (2018) who report a stagnating material intensity at the global level, and Wiedmann et al. (2015) who show that using material footprint instead of Domestic Material Consumption (DMC) cancels an only apparent relative decoupling in the US, UK, Japan, the OECD, and EU-27.

One should note that the use of certain materials do decrease along a rising GDP, even though often only locally – for example aluminium in the US between 1985 and 2009 (Zhang et al., 2017). But this is counterbalanced by either more of the same material being extracted elsewhere or other materials whose use rises even faster. For example, global amounts of extracted iron ore and bauxite have increased faster than global GDP in the 1980-2002 period (Wiedmann et al., 2015).

Energy

The case of energy is less clear cut than the one of materials. Studies diverge on their results and are difficult to compare because they measure energy consumption differently and do so at different geographical scales.

Looking at territorial final energy consumption in the 1971-2004 period, Luzzati and Orsini (2009) do not find any evidence of an Environmental Kuznets Curve, neither on a global scale nor at the level of individual countries. What they find instead is that the relation between GDP per capita and energy consumption is stable, both indicators increasing monotonically. Semeniuk (2018) uses data for 180 countries between 1950 and 2014 and finds that primary energy intensity is constant with growth. However, Csereklyei et al. (2016) find cases of only relative decoupling between primary energy consumption and GDP for 99 countries over the 1970-2011 period.

Wu et al. (2018) do find three cases of absolute decoupling (US, France, and UK) between 2005 and 2015 using production-based approaches (they use decoupling indices which do not specify how much energy consumption actually decreased) and one case of relative decoupling in Germany. Wood et al. (2018) find a relative global decoupling trend for the period 1995-2011 between final consumption and GDP. However, it is more common for authors to find situations of relative decoupling, mostly at a regional scale: Ward et al. (2016) in Australia for final energy consumption, Kovacic et al. (2018) in 14 EU countries (1995-2013) between energy consumption and hours of labor, Conrad and Cassar (2014) in Malta (1995-2012), and van Caneghem et al. (2010) in the Flemish industry (1995-2006).

Yet, as for the case of materials, a decoupling in one region often hides a recoupling somewhere else. Moreau and Vuille (2018) test this hypothesis using input-output analysis for Switzerland between 2000 and 2014. Result: the decrease in territorial final energy intensity appears to be compensated by an increase in the energy embodied in imports. Taking this into account, energy intensity remains roughly the same. In that specific study, absolute volumes increase both when measured using a territorial approach (+1%, which is the result of a domestic energy intensity decreasing by 44% being met by an increase in volume of 45%) and when using a footprint approach (+24.5%), even though the difference is significant. Examining the often-quoted relative decoupling of energy consumption from economic growth in the UK over the last 15 years, Hardt et al. (2018) show that the majority of energy intensity improvements is not due to better efficiency but instead to offshoring.

The illusion is not only geographical but also sometime sectoral. Using sectoral data for 18 EU countries between 1995 and 2008, Naqvi and Zwickl (2017) find that even though on average, relative decoupling occurs in almost all sectors, no country manages to absolutely decouple final energy use and GDP in the economy as a whole.

Lastly, that decoupling occurs during a certain period does not guarantee maintaining it over time. Analysing the Czech Republic, Hungary, Poland, and Slovakia over the 1990-2015 period, Szlavik and Szép, (2017) show that if absolute decoupling occurred at all, it lasted only during short periods and only in specific places, for example in Poland from 2011 to 2014. This ephemeral breaks in the coupling relation are most often explained by economic crises and political restructuring, and not by the continuous introduction of ever more efficient technologies and practices.

Water

Decoupling can be observed on a variety of metrics of water "use," including *water withdrawal* (also called *abstraction*), which measures the amount of water taken from a natural source (such as a lake or a river), and *water consumption*, which measures water used that will not be returned to its source, and thus not available for reuse.[18] The UNEP recently published a report entitled *Decoupling Economic Growth From Water Use And Water Pollution* (UNEP, 2015), which argues that using territorial indicators of water use, many countries have achieved a relative form of decoupling (UN-Water, 2009), and so has

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[18] Decoupling can also be observed between withdrawal and pollution, as well as on per-capita or total use within different economic sectors that use water, which we will discuss in the next part on impact decoupling.

the world as whole starting in the 1940s (UNEP, 2015, p. 12). Similar production-oriented studies show that the pace of decoupling significantly increased after the 1980s, with the global water intensity of production declining yearly by 1% from 1980 to 2000 (Dobbs et al., 2011). China is a striking example, with water consumption remaining constant since the 1980s alongside several decades of two-digit economic growth (Gleick, 2003). Some countries have even experienced absolute decoupling. This is the case of Australia that has reduced its total water consumption by 40% over the 2001-2009 period while increasing GDP by over 30% (Smith, 2011).

As promising as these numbers look, relative decoupling of water and efficiency gains were more than cancelled by the expansion of economic activities, resulting in a net increase in water consumption. Industrialising countries or regions may indeed reduce overall water use by decreasing agricultural production. Yet, decreases in agricultural production in one place require increases elsewhere, and even water-efficient industrialisation often results in a net increase in industrial water use. Even efficiency gains in agriculture may in some cases generate rebound effects resulting in net increases in water use (Loch and Adamson, 2015; Ward and Pulido-Velazquez, 2008).

A case study from Tianjin City (China), touted as the world's largest Eco-City and a blueprint for sustainable urbanisation worldwide (Baeumler et al., 2009), is a perfect example of a relative decoupling that still results in an overall increase in water consumption. According to recent research by Wang and Li (2018), the city's industrial water use and rapid economic growth are still tightly coupled, and perhaps even increasingly so. Data from 2005-2015 indicate that even though the average growth rate of industrial water consumption (+0.18%) was lower than GDP growth (+15.42%), periods of more rapid economic growth were marked by a stronger coupling with industrial water consumption.

Just like for materials, it suffices to look at global consumption to realise that gains in efficiency are being trumped by increases in volume. On a global level, Wada and Bierkens (2014) estimate that human water consumption increased more than two-fold (~250%) between 1960-2010, the bulk of which is attributable to the expansion of irrigated agriculture. With regards to global water withdrawal, the AQUASTAT database of the Food and Agriculture Organisation (2016) shows a slightly smaller expansion from 2,500 km^3/year in 1960 to nearly 7,000 km^3/year in 2010. In parts of Australia and California where absolute decoupling can be observed, water consumption remains at unsustainable levels, as evidenced by an increasing number of "anthropogenic droughts" (AghaKouchak et al., 2015; Ashraf et al., 2017). These should be seen as cases of insufficient decoupling.

Another remark has to do with the water embodied in trade. Similarly to the question of embodied energy, most decoupling studies on water do not account for so-called "virtual water" (Allan, 1998) which is the water embodied in products (e.g. one kilo of beef requires around 15,000 litres of water over the full chain of production). Affluent countries decrease their domestic water consumption by importing water-intensive products from abroad, effectively shifting their water footprint and all its relative environmental issues onto other countries.

Studies that account for "water footprint" (Hoekstra, 2017) find that affluent countries facing water-scarcity tend to reduce local water consumption by importing virtual water (Oki et al., 2017). In a cross-national study, Wang et al. (2016) confirm that the decoupling of domestic blue water use and economic growth in high-income nations occurs through virtual water flows embodied in trade. The same result stands for Feng and Hubacek (2015) who used a multi-region input-output analysis to understand global virtual water flows, as well as for other studies that attempt to measure this externalisation of water footprint (Fulton et al., 2014, 2012; Katz, 2008). Importing water-intensive services, commodities and energies can create conditions of geopolitical instability. For those concerned with global water risk and the implications for water justice, the sacrifice of one watershed for the health of another runs counter to the understanding and promise of global water decoupling.

2. Impact decoupling

Greenhouse gases

The case of carbon dioxide is the most ambiguous of all and requires a detailed discussion. Most studies do find patterns of relative decoupling in early industrialised countries and beyond – e.g. 79 countries in Lonhofer and Jorgenson (2017) looking over the 1970-2009 period.[19] Some studies even point to cases of absolute decoupling, albeit most often during short periods, only in specific locations, and often using production-based (territorial) indicators. This could be cases for rejoicing, but unfortunately, the magnitude of the decrease in emissions is negligible. Overall, the reviewed literature converges in saying that there has never been a global pattern of absolute decoupling of CO_2 from economic growth.

But let us look into the details starting with the Environmental Kuznets Curve literature. If at all, the existence of an EKC for CO_2 emissions can only be confirmed within single studies (Azam and Khan, 2016). The three meta-analyses we have screened do not find any evidence for decoupling over the 1995-2005 period.[20] Out of 588 observations, Li et al. (2007) do not find a single case of absolute CO_2 decoupling over the 1995-2005 period. What they do find is an EKC for more local greenhouse gases (such as SO_2, NOx, CO, NO_2, and SOx) but at an income turning point of 37,000 US$ per capita, which is seven times larger than the 2000 world average GDP per capita and thus practically unattainable if we aim at staying under the 1.5°C global warming target. Koirala et al. (2011) mobilised around 900 observations from 103 studies for their meta-analysis, and, fail to identify any carbon EKC. The most recent review in date, from Mardani et al. (2019), points in the same direction. After reviewing 175 studies over the 1995-2017 period, they conclude: “While this [decoupling] has happened in absolute terms in a few countries, the main trend in most developed countries is that emissions are increasing, or stabilizing at a high level. One can hardly claim that there is enough empirical evidence to assume that there is an EKC for CO_2 emission intensities.”

Absolute decoupling can be spotted only by restricting the scope of observation, that is by narrowing down either the study period or the geographical perimeter. For example, Chen et al. (2018) analyse

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[19] Also Conrad and Cassar (2014) for Malta (1995-2012); Jiang and Li (2017) for several short periods in the US; Marques et al. (2018) for Australia (1975-2016); Wu et al. (2018) in eight high-income and middle-income countries (1965-2015); and Wood et al. (2018) on a global scale.

[20] Regarding a methodological quality of EKC studies Galeotti et al. (2006) show that data sets have negligible impacts on the results. However, attention should be given to econometric misspecifications. Itkonen (2012) and Wagner (2008) find that a wrong application of methods often leads to omitted bias and thus to false statements – similar critics have previously been formulated by Stern (2004).

the total emissions of 30 OECD countries between 2001 and 2015. What they found is that GDP increased by 70.6% over the period with CO_2 emissions decreasing by 3.8%, with most of that drop taking place between 2010 and 2015. The European Environmental Agency (EEA) reports a 22% absolute carbon emission reduction between 1990 and 2017, an average of 49 $MtCO_2e$ per year (EEA, 2018). Madaleno and Moutinho (2018) find evidence for temporary absolute decoupling in the EU-15 for territorial emissions, but only between 1996 and 1999 (the whole study period was 1995-2014). Similarly, Roinioti and Koroneos (2017) found two incidences of temporary absolute decoupling, lasting one and two years respectively for the case of Greece in between 2003 and 2013. Cansino and Moreno (2018) find an absolute decoupling effect in Chile, but only for specific years of their study period (1991-2013).

Cases of absolute decoupling are more likely to be observed looking at geographically restricted areas and disregarding relations and exchanges with the rest of the world. Focusing on eco-efficiency indicators for industries in Flanders, Van Caneghem et al. (2010) report an observed absolute decoupling between 1995 and 2006. The study of Azam and Khan (2016) indicates an absolute decoupling between territorial emissions and GDP happened in Tanzania and Guatemala using annual production-based time-series data from 1975-2014. Further evidence is brought forward by Lean and Smyth (2010) for Singapore using production-based measures between 1980 and 2006.

Four remarks on these results. First, if there is absolute decoupling, it remains infinitesimal. For instance, 3.8% in 14 years (Chen et al., 2018) is a meagre performance – that is a compound annual growth rate of -0.28% per annum, which remains 18 times too slow compared to the IPCC (2018) 1.5°C target of a yearly 5% decrease. The 8% decrease in emissions between 2007 and 2015 reported by the International Energy Agency is only a yearly abatement of 1% (IEA, 2016); and the decoupling in the EU reported by the EEA would need to be increased 5-fold as to meet a -95% mitigation target for 2050. Other similarly discouraging rates of absolute decoupling are found by Pilatowska and Wlodarczyk (2018) in Belgium, Denmark, France, and the UK (1960-2012). In their comparative study, the strongest effect was in Denmark with minus 1.8% of emissions yearly alongside a 1.16% rise in GDP. As encouraging as this might look, according to the IPCC (2018), it would need to be 3 times faster and occurring simultaneously in every single country to stay within the 1.5°C limit to global warming. All of this calls for an acceleration of efforts. And yet, studies point to the opposite: the speed of decoupling in high-income countries is decelerating (Fosten et al., 2012) as the set of easy to implement measures is increasingly depleted. This is also in line with current policy impact projections of the EEA (2018).

Second, even if decoupling can be spotted over a certain period, it is likely to disappear if one extends the timeframe of the study. Wang et al. (2018) do observe several periods in the US where energy-related CO_2 emissions decline alongside a growing GDP: -1.75% (2000-2001), -1.61% (2005-2006), and between -2 and -3.31% (2010-2012). If the study had only looked at these periods, then one would speak of a clear absolute decoupling. Yet, spread over a longer period (2000 to 2014 in their study), the decrease of emissions is still absolute but averages 0.006% per year, which is about 833 times too slow compared to IPCC recommendations. Besides, an important reason for the decline was the switch from coal to gas, a one-off measure facilitated by the temporary boom of shale oil and gas in the US, which cannot constitute a permanent trend.

Third, most of these studies only take into account production-based measures. In contrast, the ones that take a consumption-based perspective find considerably different results. The most recent long-term climate strategy put forward by the European Commission states that Europe has managed to successfully decouple greenhouse gas emissions from economic growth in the past decades (European Commission, 2018).[21] However, this includes only territorial emissions and not consumption-based emissions including emissions embedded in international trade. According to van de Lindt et al. (2017), while territorial emissions declined by 13% during 1990-2010, the carbon footprint in the same period increased by 8%.

Likewise, Jiborn et al. (2018) show that Sweden and the UK (1995-2009) fall off the absolute decoupling list when carbon leakage is considered (see also results by Hardt et al., 2018 above). What remains is relative decoupling: a rise in GDP (2.9% per year for the UK and 3.2% for Sweden) comes with a smaller rise – but rise nonetheless – in emissions (1.8% per year for the UK and 1.3% for Sweden). Cohen et al. (2018) reach the same result for the UK and France (1990-2014); if consumption-based greenhouse gas emissions are accounted for on a footprint basis, absolute decoupling disappears (the exception is Germany due to high emission exports from the automotive industry). Same case for Singapore, for which Schulz, (2010) contrasts the result of Lean and Smyth (2010) showing that decoupling is only relative once indirect trade-related emissions are taken into account.

Even only in terms of relative decoupling, the difference is important. Cohen et al. (2018) identify twelve countries in situations of relative decoupling (Brazil, Mexico, Turkey, Korea, South Africa, Indonesia, India, China, Canada, Japan, Australia, and the US) while considering territorial emissions, but only two (UK and France) while measuring greenhouse gases footprint. Storm and Schröder (2018) analyse data from 61 OECD countries during 1995-2011 in search for carbon Kuznets curves. What looks like decoupling in production-based CO_2 emissions (with a turning point at US$ 56,000 annual per capita income) ceases to be so when accounting for imported carbon (turning point at US$ 93,000, which is outside of their sample).

At last, one should take into account the Global Financial Crisis of 2007-2008 and the following Eurozone Crisis for their consequences on economic activity and therefore emissions. The rapid decrease of emissions during the crisis is of little surprise. Most studies decomposing the effects of different variables on CO_2 emissions (energy consumption, energy intensity, carbon intensity, GDP) conclude that GDP is one of the biggest drivers of CO_2 emissions (Cansino and Moreno, 2018; Chen et al., 2018; Jiang et al., 2016; Madaleno and Moutinho, 2018; Roinioti and Koroneos, 2017). The review of 175 studies by Mardani et al. (2019) even points at a bidirectional coupling between GDP and CO_2 emissions. Even though a recession perhaps reduces impacts in the short term (Declercq et al., 2011; Feng et al., 2015; Roinioti and Koroneos, 2017), it can hardly be considered a policy success in terms of decoupling for green growth advocates.

To finish, let us scrutinise a specific decoupling study that was widely spread in the media. In 2016, the World Resource Institute (WRI) posted an entry on its website titled "*The Roads to Decoupling: 21 Countries Are Reducing Carbon Emissions While Growing GDP*" (Aden, 2016). To be precise, they show

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[21] The Sustainable Development Goals reflection paper (European Parliament, 2019) does speak of a consumption-based absolute decoupling while referring to the analysis of its long-term strategies (European Commission, 2018). Besides that claim, however, we have found no trace of any supporting evidence in either of these documents.

evidence for an absolute decoupling of GDP from territorial greenhouse gas emissions between 2000 and 2014 in the case of 21 countries. Even if one takes these results at face value, the decrease in emissions remains too small. Following their estimation, the fastest decoupling country is Denmark with a 30% cut over the period. While 30% may seem impressive, it is only a compounded 2.5% yearly decrease, which is half of what the IPCC recommends. The average reduction for the 21 countries is 15% in 14 years (1.15% per year, still four times too slow for the IPCC (2018) standards of 5% reduction per year).

This number gets considerably lower when one considers footprint emissions. Evans and Yeo (2016) redo the calculation with consumption-based indicators. Three countries (Slovakia, Switzerland, and Ukraine) exit the list. The Danish emissions mitigation effort shrinks from 30% to 12%. While the average reduction for the 20 countries that achieved territorial decoupling (we have removed Uzbekistan for which there is no footprint data available) is of 15.75% in total over the period, the footprint decoupling is only 7.46% (that is 706.7 Mt of CO_2 saved in 14 years) namely a compounded 0.55% yearly drop in emissions. And again, we should remember that these are the most successful nations in terms of mitigation and that the rest of the world remains on a path of increased GDP increased emissions.

These numbers should be read carefully as the calculation of footprint emissions is only nascent and extremely complex (Sato, 2014). Considering non-existing data and the level of sophistication of current models, it is more likely to under-estimate emissions than the opposite. For example, emissions from aviation and shipping are systematically excluded from national accounts. In the EU28 (plus Iceland, Norway, Switzerland), CO_2 emissions from aviation alone have been estimated at 151 Mt in 2014; although they have only increased by 5% since 2000, they are expected to rise another 45% until 2035 (EASA-EEA-EUROCONTROL, 2016). Assuming a yearly 150 Mt amounts to 2100 Mt of CO_2 emitted over the 2000-2014 period, which is three times all the emissions that were saved through absolute decoupling in Evans and Yeo (2016) footprint recalculation of the World Resource Institute Study (Aden, 2016).

Land

There are very few empirical studies that have tested the decoupling hypothesis choosing land measures as environmental variables. And yet, one can find ample evidence in related literature that, with growing income, the living space per capita is increasing, and with it the area of sealed soil. Thus, this section focuses on general relations between GDP and land use.

In the literature different definitions are used to describe land use. Weinzettel et al. (2013, p.433) refer to it as “use of land and ocean area through international supply chains to final consumption, modelling agricultural, food, and forestry products”, which is measured either by land use (gha/capita) or by the fraction of global total footprint (%). Another measure is the Human Appropriation of Net Primary Production (HANPP). The last term is the total carbon produced annually by plant growth, while the first term accounts for harvested biomass and human-induced land use change (Krausmann et al., 2013). Further measures are for example the ecological footprint (Bagliani et al., 2008; Borucke et al., 2013; Caviglia-Harris et al., 2009). Other papers only refer to single variables like croplands (Sandström et al., 2017; Tilman et al., 2011) or forests (Kumar and Aggarwal, 2003).

The existing literature does not provide any indication of an absolute decoupling of economic activity and land use, only relative ones. Conrad and Cassar (2014) find evidence for a relative decoupling of the land area affected by development from GDP in Malta between 1995 and 2012. Globally, the ecological footprint has grown together with economic growth, showing no signs of decoupling (Bagliani et al., 2008; Caviglia-Harris et al., 2009). Krausmann et al. (2013) find that while the human population has grown fourfold and economic output 17-fold, global Human Appropriation of Net Primary Production has only doubled, due to considerable efficiency gains between 1910 and 2005. For different measures and regions, these relative trends are also supported by other studies (Conrad and Cassar, 2014; Kastner et al., 2014; Tilman et al., 2011; Weinzettel et al., 2013), but no absolute decoupling can be observed.[22] Let us take cropland as an example. At the global level, cropland area harvested for food production increased by 32% from 1963 to 2005 (Kastner et al., 2014), mostly driven by increasing animal calorie demand, being itself strongly influenced by per capita income (Tilman et al., 2011). Weinzettel et al. (2013) state that for each doubling of income, the land footprint increased by 35%.

Not only does income correlate with land use, but it also does with the net displacement of land, which is why footprint indicators are of great importance to understand the relation of economic activity and land use. When trade is taken into account, high-income countries use more biologically productive land per capita than low-income countries (Weinzettel et al., 2013). EU's land footprint was 2.5 global hectares (gha) per person compared to a global average of 1.2 gha per person and total biocapacity of 1.8 gha. For each additional US$ 10,000 income per capita, between 0.1 and 0.4 gha per person are displaced outside the consuming country (Weinzettel et al., 2013), this result is supported by other studies (Kastner et al., 2014; Yu et al., 2013). In total 60% of land is used for exports (Weinzettel et al., 2013) whereas high-income countries are the greatest net importers. For example, 33% of total land use for US consumption purposes is displaced from other countries – this ratio becomes much larger for the EU (more than 50%) and Japan (92%) (Yu et al., 2013). An average EU citizen in 2004 led to an appropriation of 2.53 gha compared to a global average of 1.23 gha (Steen-Olsen et al., 2012).

Agricultural production is coupled with environmental pressures and the displacement of land via international trade means that ecological costs are also displaced (Lambin and Meyfroidt, 2011; Tukker et al., 2016; Weinzettel et al., 2013; Yu et al., 2013). The EU crop and livestock imports are a significant driver of global deforestation over the period 1990–2008; for example, more than 90% of Finland's impacts on biodiversity occurs elsewhere via its imports (Sandström et al., 2017). The associated changes in land use are expected to increase greenhouse gas emissions, about one quarter of which already results from land use and land use changes (Tilman et al., 2011). Schreinemachers and Tipraqsa (2012) find that the use of pesticide, herbicide, and fungicide does not go down as countries reach higher incomes, and remains strongly associated with crop output. What this shows is that the relation of economic activity with land use also links to other environmental challenges, such as biodiversity loss, water scarcity, climate change and energy consumption.

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[22] A closer look to countries' ecological footprint and their available biocapacity points out an interesting case of Finland, which ecological footprint decreased by 6,5% during 2002-2005, while the GDP increased by 9,5% in the same period, whilst also remaining within the limits of available biocapacity (Mattila, 2012). However, this is mainly due to wrong accounting, as Mattila (2012) showed.

Water pollutants

The aforementioned UNEP report draws on water decoupling or “dewatering” research that explicitly does not account for water pollution (UNEP, 2015, p. 2). While major advances have been made in limiting water pollution in industrial and agricultural production, the contamination of water remains a global issue that contributes to increasing global water pollution hotspots (Strokal et al., 2019). Most of the global water pollution is from the production of industrial and agricultural commodities for regional and global trade (Liu et al., 2017; Mekonnen and Hoekstra, 2016; Vörösmarty et al., 2015; Zhao et al., 2016, 2015).

The concept of return flow, that is the difference between withdrawal and consumption, is critical to our understanding of water pollution. Return flow concentrates the pollution impacts of water-dependent production. Cleaning up return flows can be achieved by advances in cleaner production technologies, often prompted by the creation and enforcement of environmental regulations. These technologies have high costs, which can prompt the movement of production to areas with fewer or less enforced environmental regulations related to water pollution. As noted in Schwarzenbach et al.’s (2010) review of global water pollution and human health, cheap production in emerging economies continues to be associated with high levels of water pollution. Outsourcing toxic and water-intensive production can lead to local, regional, and national decoupling of economic growth from impacts to basin-level water quality, however, on a global scale, the problems of water quality remain the same or are in some cases exacerbated (van Vliet et al., 2017).

Nitrogen and phosphorus accumulation, the two main macro-nutrients needed for agricultural production, lead to eutrophication and dead zones in water ecosystems, which have spread exponentially since the 1960s (Diaz and Rosenberg, 2008). Nitrogen is also released in the atmosphere, wherein reactive form it has a higher greenhouse gas effect than carbon dioxide. N and P fertilizer use rates per unit cropland area increased by approximately 8 times and 3 times, respectively, since the year 1961 (Lu and Tian, 2017). According to Lu and Tian (2017) fertilizer ratio increased by 0.8g N/g P per decade during 1961-2013, having human-derived implications on climate change, water quality and ecosystems, food security and agro-ecosystems at large. Furthermore, the recent outlook on fertilizer demand shows that nitrogen fertilizer demand is still growing even in the rich countries, North America and Europe (FAO, 2017).

Global biochemical nitrogen and phosphorus flows have transgressed their planetary boundaries (Steffen et al., 2015). This results mainly from the prevalent high-input agriculture and intensive livestock farming, which lead to atmospheric nitrogen pollution and coastal marine eutrophication and dead zones (Bouwman et al., 2013). Agricultural nutrient discharge is the most significant contributor to groundwater and surface water contamination, much larger than urban point sources (Billen et al., 2013). A study exploring changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over 1900-2050 period shows that anthropogenic N and P inputs have grown five-fold since pre-industrial times and by 2050 surpluses are expected to further increase by over 20% for N and over 50% for P (Bouwman et al., 2013).

Biodiversity loss

Biodiversity is difficult to measure,[23] but neither individual nor aggregated indicators of the state of biodiversity showed significant improvements in their rates of decline, while all pressure indicators showed increasing trends, with none significantly decelerating (Butchart et al., 2012). The last report to date by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019) has shown that almost all drivers of biodiversity loss keep increasing, that the dangerous decline of biodiversity is unprecedented, that the species extinction rates are accelerating and that the current global response is insufficient. Going in the same direction, the EU 2030 outlook for ecosystem conditions and services and the Food and Agriculture Organisation (FAO) report worrying levels of species decline (EEA, 2018; FAO, 2019, p. 445). Analysing extinction rates in comparison to natural average background rates since 1500 AD, Ceballos et al. (2015) find that current rate vastly exceeds the natural average, and warn of an impending sixth mass extinction (see also Barnosky et al., 2011).

The empirical literature on EKC relationships between biodiversity and economic growth is scarce but consistent. The first meta-analysis used 121 observations gathered from a set of 25 studies and 11 environmental indicators, including deforestation (Cavlovic et al., 2000). The study analysed the EKC relationship and estimated hypothetical income turning points using different modelling methods. For deforestation, which is used as a proxy of biodiversity loss,[24] the income turning point was estimated in the range of US$ 5000-20,000 (in 1999 prices).

Koirala et al. (2011) used almost 900 observations from 103 studies for their meta-analysis and disaggregated environmental quality measures into 12 different variables and did not observe any EKC either for deforestation or landscape/habitat degradation. Dietz and Adger (2003) do not find any EKC for deforestation and species richness, a result confirmed by Mills and Waite (2009). Even stronger is the argument by Asafu-Adjaye (2003) who finds an inverse relationship between economic growth and species diversity – a result confirmed by Raymond (2004) in a study of 142 countries. Mozumder et al. (2006) reject the EKC hypothesis for income and biodiversity risk. Using the same model, Tevie et al. (2011) reach the same conclusion in their study of 48 American states. Naidoo & Adamowicz (2001), using data from over 100 countries, investigated the link between numbers of threatened species and per capita income growth. After dividing species into seven taxonomic groups (plants, mammals, birds, amphibians, reptiles, fishes, invertebrates), they found support for absolute decoupling only for birds. Meanwhile, for plants, amphibians, reptiles, and invertebrates the relationship was the opposite, their number of threatened species increased with GDP.

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[23] Vačkář et al. (2012) provide a comprehensive review of different indices monitoring human impacts on biodiversity. One of the most known is the Living Planet Index, which shows the change in species abundance and distribution. The other indicators are: Red List Index measuring changes in extinction risk (collected by IUCN) Marine Trophic Index that is specialized for marine biodiversity, the Natural Capital Index, comprised of changes in ecosystem quantity and quality, the Biodiversity Intactness Index, measuring both species richness and population abundance, and Index of Biotic Integrity, which evaluates ecosystems in comparison to a reference state according to various human impacts (Vačkář et al., 2012). Another index is National Biodiversity Risk Assessment Index (Reyers et al., 2018), which is not updated regularly.

[24] One should be cautious with data inference and interpretation. For instance, per capita income does seem to correlate with state-protected land area, however, rather as part of various socio-economic indicators (social, economic, cultural and natural) than independently on its own (Dietz and Adger, 2003). In addition, protected areas do not guarantee higher conservation of biodiversity (Bruner et al., 2001). In some previous studies that have detected EKC (Bhattarai and Hammig, 2001), the problem may be in how biodiversity is interpreted. Reforestation through plantations does not equal to the deforestation of primary rainforests with its accompanying species. Meanwhile, McPherson & Nieswiadomy (2005) identified an EKC for threatened bird and mammal species (using IUCN data for 113 countries in 2000), and a potential turning point at around US$ 10,000-15,000 (US$ 1995 PPP) in per capita income, after which the percent threatened falls. However, the problem with the IUCN data is that the rate of endangered species or the rate of deforestation may be low in countries which has already experienced much extinction or deforestation in the past (McPherson and Nieswiadomy, 2005). Hence, they use per cent instead of the number of species and do a range of other corrections to the dataset.

Conclusions for Section 2

In light of the present review, we can safely conclude that there is no empirical evidence supporting the existence of a decoupling of the type described as necessary in the first section of this report – that is an absolute, global, permanent, and sufficiently fast and large decoupling of environmental pressures (both resources and impacts) from economic growth. In the end, our search for robust evidence was unsuccessful, coming up only with a handful of methodologically peculiar exceptions, most often of relative decoupling, and if absolute, mainly temporary and restricted in space, only for territorial indicators (that is to say spatially inconsistent), or having to do with specific local, short-term pollutants. In all cases, the reduction in environmental pressures falls short of current environmental policy targets. After such an extensive search, it is safe to say that the type of decoupling acclaimed by green growth advocates is essentially a statistical figment.

Yet, even though the success of the green growth strategy is nowhere to be seen, this lack of empirical support does not allow to completely dismiss the decoupling hypothesis. The adequate decoupling of economic activity and environmental pressures remains theoretically possible if resource productivity grows sufficiently faster than GDP permanently and globally. This might happen, some argue, by increasing the geographical coverage of emission trading systems (Stiglitz et al., 2017) in combination with phasing out subsidies for fossil fuels (Schwanitz et al., 2014), directing investments into sustainable infrastructure (Guivarch and Hallegatte, 2011), and a number of other decoupling policies (Smith et al., 2010; UNEP, 2014a). What is at dispute is the impact of a number of factors, trends, and phenomena that would enable or prevent such an efficiency-driven decoupling from happening. Putting the decoupling hypothesis in perspective with the potential impact of those factors is the objective of the final section of this report.

III. Is decoupling likely to happen?

Looking for evidence, we found that the type of decoupling that would be needed to effectively and equitably mitigate climate change and address other environmental crises is nowhere to be seen. Yet, lack of empirical support does not suffice to fully dismiss the possibility of decoupling, which some argue could well happen in the future with the right set of policy changes. The purpose of this section is to assess the validity of this position. Our claim is the following: adequate (i.e. absolute, permanent, and sufficient) decoupling is extremely unlikely to happen in the near future. We offer seven reasons in defence of that proposition: (1) rising energy expenditure, (2) rebound effects, (3) problem shifting, (4) the underestimated impact of services, (5) the limited potential of recycling, (6) insufficient and inappropriate technological change, and (7) cost-shifting. In what follows, we go through each of these reasons.

1. Rising energy expenditure

The availability of natural resources does not only depend on their absolute quantity (how much is "out there") but also on their quality and accessibility (how much effort is required to extract them). When extracting a resource, cheaper options are generally used first, which means that most readily available energy and material resources mobilised by the economy have already been exploited.[25] The extraction of remaining stocks then becomes a more complex, more technology demanding,

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[25] The common-sense idea that easiest and cheapest options are generally used first (the proverbial "reaping the low hanging fruits") is referred to in economics as the "law of increasing marginal cost" and, when applied to resources, is sometimes called the "best-first principle." Such a rule of thumbs applies widely and can be easily observed in multiple situations: from resource extraction to efficiency gains and pollution abatement.

more socially disruptive hence generally more expensive, more resource- and energy-intensive and polluting process resulting in a rising total environmental degradation per unit of resource extracted. This is the case for low-concentration metal and mineral depots, tar sands, deep off-shore wells, stocks located in polar regions or near densely populated cities like shale gas near Paris. These increasing energetic costs[26] of extraction means that more intermediate resources are necessary to extract the final resources required for the production of the same quantity of goods and services, leading to the opposite of decoupling.

The energy expenditure argument is sometimes counteracted by those insisting that energy only plays a small role in economic activities. And indeed, from a monetary point of view, the energy sector often accounts for a small fraction of total GDP. Yet, this perspective has been challenged by several scholars (Ayres and Warr, 2009; Georgescu-Roegen, 1971; Giampietro et al., 2011; Hall and Klitgaard, 2012; Kümmel, 2011). Latest to date, Keen et al. (2019, p.41) argue that energy is not a substitute to labour or capital but precisely what enables these factors of production to perform useful work – “labour without energy is a corpse, while capital without energy is a sculpture” (Keen et al., 2019, p. 41). Here, common sense is perhaps more useful than economics: the average speed of a car (GDP growth) might seem to determine its gasoline consumption (energy use), but no one can reasonably assume that a car could run without it (Fizaine and Court, 2016, p. 173).

Energy

When it comes to energy resources, the efficiency of extraction can be quantified using the concept of EROI (or EROEI), which stands for Energy Return on Energy Invested. EROI is the ratio of the quantity of energy obtained from a resource to the quantity of energy that must be spent to extract it in the first place.[27] It is a measure of *net energy output*; for instance, a ratio 1:1 for petroleum would mean that it takes a barrel of oil to extract another barrel of oil while a ratio of 10:2 would mean that the energy costs of extracting 10 barrels are two barrels. This concept differetiates the *cost* and the *surplus* of energy (e.g. an EROI of 50:1 means an energy cost of 2% for an energy surplus of 98%, while one of 5:1 means a cost of 20% for a surplus of 80%). The lower the EROI, the higher the *energy cost* or *energy expenditure*. A declining EROI means that an increasing portion of energy output must be allocated to obtaining energy, which means an increase in resource use and impacts.

Several authors make the empirical claim that high levels of energy expenditure are associated with low economic growth rates, or even that GDP cannot grow over a certain threshold of relative energy expenditure: 5.5% of total GDP for Murphy and Hall (2011) looking at the US between 1970-2007;

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[26] It should be stressed that there is a difference between the cost and the price of a natural resource. Let us take energy as an example. Whereas the price denotes the quantity of money that a commodified form of energy commands on the market (e.g. 55€ for a barrel of oil, 0.2€ for one kWh of electricity), its cost (as used in this section) refers to the real (and not monetary) quantity of energy (e.g. litres of petroleum, cubic metres of gas, calories of food, kilowatt-hours of electricity, kilos of coal or biomass) that must be spent in order to extract one extra unit of energy. Another way to put it is that the costs of a natural resource has to do with its extraction and production whereas its price has to do with its consumption. Because such resource expenditures are usually priced as well, the cost and the price of a natural resource tend to converge in the long term.

[27] Hall et al. (2014) differentiate between four types of EROI. “Standard EROI” is the energy output divided by the sum of the direct and indirect energy used to generate that output. “Point of Use EROI” adds the costs associated with refining and transporting the fuel. “Extended EROI” considers the energy required not only to get but also to use a unit of energy. And finally, “societal EROI” is “the overall EROI that might be derived for all of a nation’s or society’s fuels by summing all gains from fuels and all costs of obtaining them.”

8-10% for the US and 9-11% for the broader OECD in Bashmakov (2007); and 11% for Fizaine and Court (2016) looking at the US over the 1850-2012 period. The logic is simple: if energy expenditures exceed these thresholds, it starts to act as a limiting factor on employing labour and capital.

The EROI for fossil fuels is of special interest as it also describes how much greenhouse gas emissions are generated in a fossil fuel-based economy to provide one additional unit of fossil energy (ton or barrel) – one could even speak of the *climate cost* of extracting a barrel. While the carbon intensity of that consumption is fixed (e.g. burning one barrel of oil emits around 120 kg of carbon), a decreasing EROI means an increase in emissions per unit of primary energy used (the carbon emissions corresponding to the increasing extra energy burnt to extract that barrel adds up to the 120 kg). According to some estimations, the EROI for the global production of oil and gas increased from 23:1 in 1992 to 33:1 in 1999 and declined to about 18:1 in 2005, giving credence to the theory that the efficiency gained by technical improvements is being trumped over time by depletion (Hall et al., 2014). Certain authors such as Morgan (2016) now speak of an "energy sprawl" to describe the necessary expansion of the infrastructure required to access energy and the growing proportion of GDP that it will absorb. Accounting for both fossil and renewable energy sources, Capellán-Pérez et al. (2018) find that the EROI of the global energy system went from 7:1 in 1995 to 6:1 in 2018.

A prime example of this process of increasing marginal costs concerns the extraction of different types of unconventional oils. Tar sands and oil shale deliver a mean EROI of 4:1 and 7:1 (Lambert et al., 2014). Shale gas is often acclaimed as an abundant alternative to oil, especially in the US (Moeller and Murphy, 2016), but not only is drilling shale wells relatively more expensive in both energetic and financial terms, but the rates of decline in production tend to be significantly faster than traditional oil wells (Morgan, 2016, p. 63).

Another example is coal. Putting pollution issues to the side for a moment, global reserves of coal suggests that, in terms of volume, coal is still relatively abundant. Yet, not all forms of coal are equal in quality. Anthracite, which is the richest coal in terms of energy content, is increasingly scarce, pushing coal companies to extract bituminous and sub-bituminous coals of lesser energy density (Kerr, 2009; Morgan, 2016; Schindler and Zittel, 2007).

One could argue that green growth would only run on renewable energies and so that the EROI of fossil fuels is irrelevant. Even though we will shortly argue that it is not, let us assume for a moment that a complete replacement of fossil fuels by renewables is possible materially (finding enough minerals and land to build the energy infrastructure) and socioeconomically (having renewable energies finding social acceptance and investment resources to completely replace fossil ones). Even then, according to Murphy and Hall (2011), the EROI of renewable energies (below 20:1) is still significantly lower compared to the high EROIs during the early days of fossil fuels (Hall et al., 2014). Capellán-Pérez et al. (2018) simulate what would happen to average EROI by 2050 should renewable energy sources increase from 15% to 30% (1st scenario) and from 15% to 50% (2nd scenario). In the first scenario, average EROI drops from currently 6:1 to 5:1; and down to 3:1 in the second scenario. If energy expenditures play an important role in the dynamics of economic growth, this means that renewable energies are fundamentally unable to propel an economy as fast as fossil fuels.

Materials

Similarly, and for the same kind of reasons, the rule of increasing marginal costs or the *best-first principle* applies to material extraction. A series of studies already show how the quality of ores of essential minerals are declining (e.g. Calvo et al., 2016). Lower ore grades mean more overburden and environmental damage.

The average concentration of copper in ore/mined material went from 1.8% in 1930 to 0.5% today (Arnsperger and Bourg, 2017, p. 87), a situation that is common to other minerals. Lower concentration rates for minerals means that higher volumes of materials need to be mined and displaced to extract the same amount of ore and with it more energy. In the first UNEP decoupling report, Fischer-Kowalski et al. (2011b, p. 25) estimate that, on average, the extraction of materials today requires to displace three times more matter than a century ago.

This is particularly problematic when it comes to green technologies (Calvo et al., 2016; Valero et al., 2018). Indeed, the mineral intensity of renewable energies is higher than the one for fossil fuels – 1kWh of renewable energy requires 10 times more metals than 1kWh of fossil energy (Arnsperger and Bourg, 2017, p. 87). Add increasing production into this, and the following vicious circle emerges: more energy will be necessary to extract more minerals which are needed to build more energy infrastructure, part of which is needed to provide the additional energy required to extract more minerals and so on and so on. Renewable energies can mitigate some environmental impacts but they cannot trump resource scarcity.

What is often forgotten is that this increasing resource scarcity also translated into an ever further expansion of the so-called *commodity frontier* (Moore, 2000), that is advancements into previously untouched pristine areas, often at the cost of indigenous communities and ecosystems' health. Current examples include the extraction of tar sand in Alberta, Canada, oil in the Peruvian rain forest, or, most famously, in a national park in Ecuador. While these involve fossil fuels, the reach for the minerals required to build renewable energy infrastructure poses a similar threat to socio- and biodiversity.

Energy and material are crucial for the functioning of an economy, and even more so for one that is growing. Just like a living organism, an economy requires energy and material not only to grow but also only to maintain its current size. All available evidence points towards increasing costs of extraction for both energy sources and materials. If economic growth requires more energy and material, and it takes increasingly more energy and material to extract energy and material, then rising energy expenditure acts as a limit to growth and constitutes a barrier to decoupling. In order to argue that decoupling is possible, one must show how to deal with the increasing marginal cost of energy and material extraction.

2. Rebound effects

Improving resource efficiency is probably the most common argument put forward in defence of decoupling. However, every action that responds to savings in resources is prone to *rebound effects*, that is a difference between the projected and the realised environmental savings from an efficiency improvement. Such a phenomenon was hinted at already in the 18th century by Stanley Jevons in *The Coal Question* (1865, pp. 140–142): "It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. [...] Whatever, therefore, conduces to increase the efficiency of coal, and to diminish the cost of its use, directly tends to augment the value of the steam-engine, and to enlarge the field of its operations" – hence the rebound effect often qualified as "Jevons Paradox" (Giampietro and Mayumi, 1998; Jevons, 1865).

This idea that efficiency changes would rebound into more consumption gained ground in the field of energy economics in the context of the oil crises of the 1970s, most notably with the work of Khazzoom (1980) and Brookes (1990) – later referred to as the "Khazzoom-Brookes postulate" (Saunders, 1992). After more than 40 years of research, the literature has expanded to encompass a variety of causes and effects.[28] In order to account for overall decoupling, the concept we find most relevant is the "environmental rebound effect" (originally used by Goedkoop et al., 1999, and then by others such as Murray, 2013; Spielmann et al., 2008; and Takahashi et al., 2004), which goes beyond energy issues to encompass a wider range of environmental concerns.[29]

Several types of rebound effects

Rebound effects come in many shades depending on whether efficiency leads to an increase of consumption of the same product or service (*direct rebound effect*), whether freed resources are allocated elsewhere (*indirect rebound effect*), or whether consumption is induced by structural changes in the economy as a whole (*structural rebound effect*). These effects, alone or together, are then either *partial* or *total* depending on the magnitude of their impact on resource use.

First-order: direct rebound effects

Direct or first-order rebound effects refer to cases where the efficiency gain is reinvested as additional consumption of the same product or service. This is especially true for normal goods for which a decrease in the cost of use perceived by users translates into higher consumption. For instance, driving a more fuel-efficient car more often, faster, or over longer distances; the petrol that was saved in efficiency by the car rebounded into more usage of the car. Direct rebound effects can also occur in production, for example when the acquisition of a more energy-efficient machine motivates additional production (*output effect*).

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[28] Here are a few examples that show the wide span of the concept: time rebound effects (Jalas, 2002), socio-psychological or mental rebound effect (de Haan et al., 2006; Girod and de Haan, 2009; Santarius and Soland, 2018), international rebound effects (Bergh, 2017).

[29] For a general framework for the study of environmental rebound, see Font Vivanco et al. (2016).

Second-order: indirect rebound effects

Indirect or second-order rebound effects refer to cases where resources freed by an efficiency or sufficiency improvement are re-allocated to another type of consumption (*re-spending effect*). For example, driving a more fuel-efficient vehicle (efficiency) or deciding to use it less often (sobriety) could save money (*income effect*), which can then be spent on impactful products or services (e.g. a far-away holiday trip by plane) or invested on problematic financial products (e.g. related to fossil fuel extraction). For producers, profits resulting from productivity gains can be reinvested into expanding production capacity (*re-investment effect*).

What Wallenborn (2018) calls "structural rebound effect" is a good example of such indirect rebound.[30] It is structural because it has to do with economic structures such as markets, ownership, and money. In a globalised economy where money can be used to buy almost anything (one then speaks of *general-purpose money*), all purchasing power is a potential polluting power. Even if euros are spent on green products, and even if the sellers of these products spend these euros in a sustainable way, at some point down the chain, these euros are likely to be used in a polluting manner. Even euros not spent will cause resource consumption and pollution when re-lent by the bank to finance new investments. The only way to avoid this effect would be to change the structure of the economic system itself (decommodification, localisation, special-purpose monies like complementary currencies, etc.).

Third-order: economy-wide rebound effects

Efficiency in resource use can also rebound at the macro-level (*economy-wide* or *macroeconomic rebound effect*). For instance, efficiency gains in internal combustion engines have helped made private car transportation effective and affordable and resulted in a wide diffusion of this technology. This generalisation of private car transport has in turn driven the spatial configuration of cities and territories, resulting in extensive spatial configurations which now rely on, and even require, the use of private cars. This wide-scale modification of the system of needs now results in a dramatically higher energy consumption from the transport sector. In other words, more fuel-efficient cars reinforce the hegemony of cars at the expense of more sustainable modes of transportation like trains and bikes. Resource efficiency can also lead to a restructuring of the economy around nature-intensive activities (*composition effect*). For example, abandoned mining activities can be resumed after the development of new efficient techniques makes it economically profitable again, as it is currently the case for gold mining where lower grade ores (including the former overburden) are now reprocessed.

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[30] In the words of Jevons's himself writing in the The Coal Question (1865): "[…] In fact, there is hardly a single use of fuel in which a little care, ingenuity, or expenditure of capital may not make a considerable saving. But no one must suppose that coal thus saved is spared – it is only saved from one use to be employed in others, and the profits gained soon lead to extended employment in many new forms. The several branches of industry are closely interdependent, and the progress of any one leads to the progress of nearly all" (Jevons, 1865: 136 cited in Missemer, 2012, p. 99).

Partial and total rebound

Depending on its magnitude, a rebound effect can result in either an overall decrease (*partial rebound*) or increase in resource use (*total rebound,* also known as *overshoot* or *back-fire*). In the first case, the savings are larger than the extra rebounded consumption (e.g. a heater consumes 50% less and rebounds in being used 1.5 times more, which means there are still 25% net savings). In the case of total rebound, however, the rebounded consumption is larger than the savings and savings are totally offset (e.g. if the money saved by using a car consuming 30% less energy per km is used to pay for a holiday trip by plane where it pays for much more energy than in the case of gasoline which unlike kerosene is heavily taxed).[31] In relation to decoupling, this means that a rebound effect can either slow down the expected rate of decoupling (*partial rebound*) or reverse it altogether (*total rebound*).

Empirical evidence of rebound

Indirect and structural rebound being highly complex, most empirical research focuses on *direct* rebound effects, which are easier to measure. In their review of energy use rebounds, Ackerman and Stanton (2013, pp. 120–121) conclude that evidence for total direct rebound effects is rare: “estimates of 10 to 30 percent seem common […] actual evidence of rebound effects of 100 percent or more appears to be non-existent.” Same conclusions for surveys conducted by Greening et al. (2000) and Sorrell (2007) who find a diverse range of rebounds, sometime low like in the case of lighting (up to 15%), moderate like in the case for aviation (19%), or very high like in the case for motorised transport (up to 96%).[32] Galvin (2014) reports a rebound for household energy conservation in the range of 0-50% for older EU member states between 2000 and 2011 – certain countries, notably Eastern European countries, as well as Finland and Denmark, show situations of total rebound. Grafton et al. (2018) show that higher use of efficient technology rarely reduces water consumption. Kyba et al. (2017) report a situation of backfire in the case of LED technology for outdoor lighting. Antal and van den Bergh (2014) estimate the re-spending rebound for saving energy from gasoline to range between 45 and 60% for large economies such as Russia, China, and India.

Magee and Devezas (2017) examine numerous statistical sources to estimate the use of 69 different materials from 1960 to 2010, arguing that the Jevons paradox applies to just about every substance. Out of their sample, they find only 6 cases of absolute decline. Four of these materials – asbestos, beryllium, mercury, and thallium – have been phased out deliberately by legal restrictions because of toxicity issues. The other two are wool, which has declined without decreasing the global populations of domestic sheep or other wool-producing animals, and tellurium, a byproduct of refining copper whose use in solar panel manufacturing means its overall consumption is likely rising again.

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[31] In the literature, and following Ehrhardt-Martinez and Laitner (2010), what we call partial and total rebound are often referred to as “typical rebound” and “back-fire.” The authors (ibid. 7-77) also add a third category: a “negative rebound” for situations where actual energy savings are higher than expected (e.g. “a family that installs a new energy-efficient water heater may be motivated to find other ways to save energy by taking shorter showers, washing clothes in cold water, or by limiting dishwasher use to full loads”; negative rebound, better example, direct causality: isolating walls reduces heating demand, making existing heating installations oversized. This, in turn, requires installing new and smaller boilers, which are more efficient, so energy demand sinks again. or on the producer side if the price of a new machine is greater than the saving in operating cost it allows). To avoid confusion, others prefer to speak of a “super-conservation” effect (Saunders, 2005) or “amplifying” and “leverage” effects (Spielmann et al., 2008).

[32] For all figures given, readers should be aware that the methodology used influences the results. For instance, studies using Life Cycle Analysis together with the concept of environmental rebound effect find a higher likelihood of backfire. This is the case for Font Vivanco et al. (2016) looking at electric cars.

Empirical studies of macroeconomic rebound effects are scarcer than their micro counterparts. In his review of the literature, van den Bergh (2017, p. 4) concludes that “the majority of economy-wide studies suggest overall rebound is above 50% and possibly much higher.” In a survey of computable general equilibrium studies, Dimitropolous (2007) finds three cases of total rebound, three others above 50%, one in the range of 30-50%, and one around 15%. Even though rebound effects of the 2ndor 3rdorder are the most determining ones, these remain the most difficult to study empirically.

The rebound effect argument minimises the plausibility of the decoupling hypothesis. Thus rebound effects must be taken into account while considering decoupling scenarios as they might make rates of resource use more or less sensitive to the introduction of resource-saving technologies and sufficiency-driven behavioural changes. The point is not to argue against those, which may still have positive overall impacts, as long as rebound effects remains limited, especially if anticipated by decision makers and counterbalanced with proactive policies. But it remains very risky to rely exclusively on sectoral and technical improvements. Rather, what is necessary is an in-depth and systemic consideration and anticipation of potential rebound effects in the design of sustainability policies.

3. Problem shifting

An additional argument to be considered alongside rebound effects is that efforts to solve one environmental problem can create new ones and/or exacerbate others. In other words, decoupling of one environmental factor can occur at the expense of the (re-)coupling of another one. As Ward (2017) points out to illustrate this argument, the world decoupled GDP growth from the build-up of horse manure in city streets and whale oil, but only by substituting it by alternative uses of nature. In what follows, we consider the example of climate change mitigation and show how four different sources of energy often considered as solutions for green growth merely change the form that the environmental burden takes, often with unintended spill-over effects.

Example 1: Renewable energy

Renewable energy is often depicted as clean and unlimited, but it is far from being free of environmental pressures. Renewable energies and efficiency-enhancing ICT technologies reduce carbon emissions but exacerbate land use (e.g. solar farms and biomass/biofuels), and water conflicts in the case of hydropower (Capellán-Pérez et al., 2017; Havlík et al., 2011; Scheidel and Sorman, 2012; Yang et al., 2012). They increase metal demand and the local conflicts associated with their extraction (Ali, 2014; Chancerel et al., 2015; Kleijn et al., 2011; Vidal et al., 2013), and, in the case of photovoltaic infrastructure, generate environmental pollution and emissions of greenhouse gases (Andersen, 2013; Hernandez et al., 2014; Zehner, 2012). The extraction of rare earth minerals, which are essential for many green technologies including windmills, causes enormous environmental damage, for example in China (Pitron and Védrine, 2018).

Let us take three more examples among many. The production of batteries for electric cars puts pressure on the extraction of lithium, cobalt, nickel, and manganese (Bednik, 2016, p. 101; Valero et al., 2018). The expansion of biomass for biofuels can encroach on protected areas and lead to an increase of monocultures, negatively impacting biodiversity and its conservation (IPBES, 2019), a good example being deforestation in the Indonesian rainforest for palm-oil plantation (Koh and Wilcove, 2008; Margono et al., 2012); and hydropower produces methane emissions when algae growth is catalysed by the silt trapped by the dam, sometimes generating more greenhouse gas emissions than a fossil-fuel-fired plant (Deemer et al., 2016).

Example 2: Nuclear energy

Nuclear energy is a good case in point. Being relatively carbon-neutral,[33] it is considered the principal factor that allowed countries like France, Sweden, the UK and Germany to reduce their energy-related carbon emissions. Nuclear energy, however, requires the extraction of uranium as fuel as well as titanium, cobalt, tantalum, zirconium, hafnium, indium, silver, selenium, and lithium for construction materials (Sersiron, 2018, p. 165). A shift to nuclear power means intensifying the coupling of economic

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[33] This remains a matter of controversy, as it is difficult to calculate the carbon footprint of the entire life-cycle of a nuclear plant, including indefinite waste storage and potential clean-up operations after accidents.

activity with various materials, starting with uranium.[34] Mining and transporting these materials is itself a source of environmental pressures, for example in terms of water pollution or biodiversity loss through land change (Conde and Kallis, 2012). Furthermore, nuclear energy involves a different set of social-ecological hazards linked with the storage of toxic waste as well as the risks of nuclear accidents and nuclear weapon proliferation. In sum, nuclear electrification shifts the coupling from one *impact* (CO_2 emissions from fossil fuel) to other *impacts* (e.g. biodiversity loss, water pollution, and other impacts related to mining and transport, toxic waste) and *resource use* (e.g. uranium scarcity).

Example 3: Natural gas

The switch from coal to natural gas is a good example of shifting problems from one greenhouse gas to another. The World Resource Institute (2016) reports a 6% fall in measured US greenhouse gases emissions between 2000 and 2014, which alongside a 28% increase in GDP appears to be a temporary absolute decoupling. This corresponds to a large shift away from coal to natural gas (Feng et al., 2015), which was lauded by public authorities for its ecological benefits.[35] The problem is that the extraction of natural gas emits methane, a gas roughly 28 times more potent at heat-trapping than CO_2 over a century (IPCC, 2013) which easily escapes into the air before it can be captured in a pipeline. Turner et al. (2016) find that US methane emissions increased by more than 30% over the 2002-2014 period, which more than cancels the drop in CO_2. Same results for Howarth et al. (2011) who show that if more than 3% of the methane from shale-drilling operations leaked into the atmosphere, this would make shale gas more climate disruptive than coal (the leaks they report are in the range of 3.6 to 7.9 per cent).[36] The problem of methane leakages goes beyond the relatively new phenomenon of shale gas extraction and concerns convention gas operations as well, especially the ones with faulty infrastructure.

What has been shown above for greenhouse gases emissions can be repeated for various other environmental issues. The point is that piecemeal solutions are likely to fall short in addressing a complex, systematic environmental crisis with many interdependent factors at play. Substituting one problem like climate change for another such as biodiversity loss cannot be considered problem solving. In order to argue that decoupling is possible, one must show that a decoupling in one type of environmental pressure will not translate into significantly increasing another type of pressure.

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[34] If only for the case of uranium, currently identified reserves – 7.6 million tonnes commercially recoverable at less than 260 US$/kgU in 2015 (OECD, 2016) –, would only allow 13 years of electricity production at current demand (Brown et al., 2018, p. 840).

[35] Closing President Trump's speech justifying the withdrawal from the Paris Agreement on June 1st, 2017, Scott Pruitt, then the administrator of the Environmental Protection Agency, announced: "before the Paris Accord was ever signed, America had reduced its CO2 footprint to levels from the early 1990s. In fact, between the years 2000 and 2014, the United States reduced its carbon emissions by 18-plus percent."

[36] This leaking issue is not unique to fracking. It also happens because of ancient infrastructure or in the case of open mines where methane is not actively captured.

4. The underestimated impact of services

Another hope for the decoupling of growth and environmental pressures lies in the tertiarisation of the economy, that is the shift from extractive industries (agriculture and mining) and manufacturing to services. This was already one of the explanations proposed by the scholars who first described the Environmental Kuznets Curve: “economic growth brings about structural change that shifts the center of gravity of the economy from low-polluting agriculture to high-polluting industry and eventually back to low-polluting services” (Panayotou et al., 2000). Indeed, the service sector as such is much (only considering direct consumption) less nature intensive than the primary and secondary one. If economic growth is mostly driven by the expansion of economic activities where the product is mostly information (e.g. finance, insurance, education), then raw materials and energy consumption as well as environmental harms can be expected to decrease We challenge the possibility for such dematerialisation-through-services on several grounds.

Relative and absolute tertiarisation

For tertiarisation to contribute to decoupling, it must translate into an absolute, and not only relative, decrease of the volume of industrial activities. A situation where the volume of services grows without a corresponding and simultaneous shrinking of other sectors may indeed be called a “relative” tertiarisation of the economy (the share of industrial activities in the whole economy decreases while its volume still increases), but one that actually results in higher environmental pressures.

With the impacts from the primary and secondary sector constant, a growing tertiary sector adds to the pressures, even though it lowers the average energy intensity per euro. In reality, this situation seems to be the rule rather than the exception.[37] The development of new types of services adds-up to other polluting activities instead of substituting to them. Consumers buy a Netflix account *with*, and not *instead*, of a computer, and workers can produce services if they are nourished, transported, and housed, not instead of food, vehicles, and homes. Immaterial products require a material infrastructure. Software requires hardware, a massage parlour requires a heated room, and the platform on which we are writing these very words requires a computer along with all the material equipment and energy necessary to make the Internet run. Services cannot be generated without raw material extraction, energy provision, and infrastructure building, all of which are tightly coupled with environmental pressures. The expansion of the service sector can hardly be decoupled because it is part of an economy that grows as an integrated whole.

To the question “do societies with a larger service sector actually dematerialise?” Fix (2019) answers an unequivocal “no.” Looking at 217 countries over the 1991-2017 period, he concludes that “the evidence indicates that a service transition does not lead to absolute carbon dematerialisation” (ibid. 4). Similarly, Suh (2006) calculates that in 2004 in the US, $1 spent on seemingly material-free services

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[37] We should also say that situations, where tertiarisation in one country occurs at the expense of (re)industrialisation in another, are equally problematic for that it only shifts the environmental burden somewhere else (we will treat this point at length in Reason 7: cost shifting).

requires 25 cents of output from manufacturing, utility, and transportation service sectors. In Denmark, Jespersen (1999) finds that, if one includes all indirect uses of energy, the service sector is actually as energy-intense as the manufacturing one. In Spain, Alcántara and Padilla (2009) find the service sector responsible for the lion's share of increases in emissions, and this because of its reliance on other, polluting economic activities.

Additionally, workers in the service sectors receive wages, which are used for purchasing material items produced in the manufacturing sectors. If the value of a dematerialised good increases, it means that the purchasing power of those who sell that good increases too (potential re-spending rebound) and that customers may work longer hours to afford it (potential re-investment rebound), both having resources implications. So the direct ecological intensity of a company specialised in internet advertisement may be relatively low, but because it provides its employee with high-salary, and additionally because the advertising that it produces fosters the consumption of material or energy intensive products and services such as cars, clothes, technological gadgets, and far-away holiday travels, its indirect ecological intensity is higher than it seems.

From an environmental perspective, not all services are equally desirable and so certain forms of tertiarisation are more desirable than others. Services in one sector do often spill over in more consumption or production in another. Think of financial and marketing activities whose purpose is to boost sales of manufactured products and investment in extractive industries. But also IT services and software development, which allows for-profit enterprises to engage in planned obsolescence, or more generally to faster upgrades in hardware. Or also of those services that rely on material and impactful tools, for example being chair-lifted up a ski slope or sky-diving from a plane. In contrast, the expansion of yoga clubs, couple therapists, and climbing centres may be less intensive on nature, even though not necessarily so (see *Services have a footprint too* just below).

Not much tertiarisation left to do

Tertiarisation only provides a partial decoupling, and, importantly, one that has already occurred in most OECD countries. In these economies, the share of services in GDP is often already high, which is problematic because these are precisely those countries which have the highest ecological footprint per capita and thus should reduce their impact the most. Countries that have already reached a high degree of tertiarisation (more than 70% of value-added is generated in the service sector) retain a small industrial part that is increasingly difficult to compress.

That is because certain sectors simply cannot be dematerialised. This is the case for agriculture, transport, and housing construction, which, are often in the top sectors in terms of emissions and used materials. Cement is a good example. Representing 5% of global greenhouse gas emissions, its production implies both high levels of process emissions and energy consumption, as well as an important amount of increasingly scarce marine sand (Rubenstein, 2012; The Pembina Institute, 2014). Although constructions can substitute other materials to cement, it is difficult to imagine how services could possibly offer adequate substitutes to most industrial production with regards to elementary needs such as food, shelter, or mobility (the service of having a pizza home delivered requires roads, a vehicle, and, not least, a pizza made from material ingredients). Hence, dematerialisation only concerns a limited fraction of the global economy, leaving most of the environmental pressures unsolved.

Services have a footprint too

Even if services are less nature-intensive than industrial goods, they still have material requirements and environmental repercussions, and so cannot be expected to fuel a biophysically unbounded process of value creation. In one of their decoupling reports, UNEP (2014a, p. 70) find a linear relation between expenditure in services and emissions of CO_2 in the direction of more services, more emissions.

Gadrey (2008) points to three factors explaining such correlation. Services require people to travel, either from provider to customer (e.g. mail delivery) or the opposite (e.g. commuting to school) which is made possible by material infrastructure, vehicles, and energy uses. Then they are often anchored in specific material spaces (university building, train station, airport, hospital, offices), whose construction, operation, and maintenance requires materials and energy. They also rely on material tools, which production and use are far from being environmentally-neutral (ICT, computers, credit card readers, screens and displays, cooling infrastructure in data centres).

In terms of materials, the making of information and communication technology products such as computers, mobile telephones, LED screens, batteries, and solar cells require scarce metals like gallium, indium, cobalt, platinum, in addition to rare minerals. An expansion of services means more transactions using more devices, which require more minerals whose extraction involves environmental impacts. Not only these material requirements imply significant environmental impact (from their mining) but their limited availability and recyclability (Reason 5) also put absolute limits to the growth of material-based services. And even if it is common to observe a decline in the number of material products needed to manufacture equipment, these efficiency gain are being trumped by growth in volume of equipment and intensity of usage (Reason 2), often having to do with decreasing lifetime due to planned obsolescence (Reason 5).

Services require energy, not only to build the material infrastructure they rely on, but also to simply run. Not only for end-user equipment (laptops, smartphones, routers) but also for the infrastructure, such as data centres and access networks (the wiring and antennas that carry data). Malmodin et al. (2010) calculate that ICT used 3.9% of global electricity in 2007, accounting for 1.3% of global greenhouse gas emissions. Numbers are similar in other studies; for instance, the information and technologies sector produced 2% of global CO_2 emissions in 2007 (830 $MtCO_2e$), half of it accounting for computers and devices and the other half for data centres and telecoms (The Climate Group, 2008). Starting from Malmodin et al.'s (2010) 3.9% of global electricity used by ICT, Van Heddeghem et al. (2014) find that it went up to 4.6% by 2012. Forecasting to 2030, Andrae and Edler (2015) estimate that ICT could consume up to 51% of global electricity, contributing up to 23% of global greenhouse gas emissions.

In itself, the Internet accounts for between 1.5 and 2% of the world's energy consumption (CEET, 2013). Only considering the users' side, the 100 most visited French website require 8.3 GWh or the energy consumption equivalent of 3,077 households (WEA, 2014). Energy consumption resulting from Bitcoin emits an annual 69 $mtCO_2$ and, if more broadly used, could alone produce enough emissions to push warming above 2°C within less than three decades (Mora et al., 2018). Carr (2006) estimates the energy consumption of a Second Life avatar to be around 1,752 kWh per year, which he compares to a world average for humans of 2,436 kWh. Looking at the ecological cost of music in the US, Devine and Brennan (2019) discover that, even though music has become almost completely digital, it is, in terms of greenhouse gases, more polluting than it has ever been: from 140 million kg in 1977 to 157 in 2000 and between 200 and 350 in 2016.

Because of the prevalence of fossil sources in the current energy mix of countries hosting data centres, ICT ends up with a heavy contribution in terms of emissions. The Greenpeace report "How Clean is Your Cloud?" (2012) finds that, for example, 39.4% of the electricity used by Facebook servers is generated by coal plants, while it is 49.7% for Apple. This energy consumption adds up to an already high level of energy demand, exacerbating the environmental impacts of the energy sector. And perhaps yes, this climate impact would disappear should all services run on renewable energy, but, assuming that this is even possible (Reason 1), then it would still generate an array of environmental issues (Reason 3).

The so-called "service economy" carries a heavier biophysical backpack than one would think. In the countries with the most urgent mitigation imperatives, the service sector has already been developed to its maximum without the benefits of absolutely decreasing environmental pressures. Services have a footprint, that even though lower than manufactured products, is often only added on top of the environmental pressure pile without many substitutions occurring. This is because the service economy can only exist on top of the material economy, not instead of it. Moreover, services such as advertising or financial products do sometimes actively foster more polluting production, which results in an overall rise in environmental pressures. Again, we are not arguing against services; on the contrary, it is crucial to replace jobs in resource-intensive sectors with more labour-intensive work. Rather, the point we make is that directly reducing output in the problematic sectors would be more effective than developing activities around them hoping that substitution would somehow occur.

5. Limited potential of recycling

Recycling is a common strategy advocated for decoupling often associated with the idea of a *circular economy*. The idea is that resource decoupling could be possible if all materials required for the production of new products were extracted from the old products that have been thrown away and not from nature. The traditional linear process of production would then be turned into a "closed-loop" (Stahel and Reday-Mulvey, 1981), "zero waste" (Palmer, 2005), "cradle to cradle" (McDonough and Braungart, 2010) economy. Of course, closing the loop between waste and extraction via recycling is a sensible goal, and in theory, one would want any economy to be as circular as possible. What we are about to argue is that there are limits to this circularity and that these limits are quickly reached in a fast-growing economy.

Recycling itself requires new materials and energy

Perpetual motion machines do not exist in reality. Even though significant gains can be expected from better recycling, the process of recycling itself necessitates energy and, most of the time, new materials, which would then also need to be recycled at some point, requiring the use of additional new material, and this *ad infinitum* (Georgescu-Roegen, e.g. 1971, p. 132, spoke of an "infinite regress"). This means that because of unescapable laws of nature (here the entropy law), the technically feasible recycling rates are always below the theoretically possible ones. On top of that, the economically justifiable rates are often significantly below what is technically possible for that the marginal cost tends to increase the more a process approaches its theoretical maximum (Reason 1).

Since materials inevitably degrade through time (2nd law of entropy), they can only be recycled into the same products for a limited number of times before they have to be used to produce other products with lower grade requirements. Put another way, sooner or later, any recycling is necessarily downcycling. For instance, plastic bottles can be recycled into plastic fibre for clothing but not back into plastic bottles, and they can finally end up in the noise protection walls along motorways. Paper cellulose fibres can only endure 3 to 6 cycles, for which they need to be mixed with new fibres, and until they become too fragile to be used for paper before being used for cardboard and later as housing isolation and finally as biofuel. Just like for energy, this wearing down of materials sets absolute limits on how circular any economy can be.

Giampietro (2019) proposes another way of thinking about it. In a way, nature already recycles all materials for free, albeit too slowly for current rates of extraction. Arguing that materials and energy will then be recycled within the economy, and not outside of it, comes with an energy price tag. As always, production requires labour, tools, and energy, except that this time, what is being produced is recycling services. Put another way, it is a use of primary energy and material to recycle waste, that is secondary energy and material. In a world where the economy is relatively small compared to its environment and where the flows of primary energy and materials are larger than the secondary flows, an economy can indeed be circular. Yet, when the scale of the second matches the ones of the first, circularity is compromised. As the author puts it: "what really matters in relation to the potential of recycling is *the size* of the required input flows and the waste flows generated by the economy (technosphere) compared to *the size* of the primary sources and primary sinks made available by ecological processes (biosphere)" (ibid. 149). If economic growth means an increase in the size of the economy compared to its environment, then it means that growing economies will sooner or later reach the limits of circularity.

Recycling rates are far from 100%

Of course, one can argue that this entropy argument is irrelevant to a situation where rates of recycling are low and that simply increasing those rates to match the pace of increase of resource use will be enough to achieve absolute decoupling. But here comes a practical consideration: How likely is it for recycling rates to increase that much?

Let us first assume that recycling does not require extra energy and that all materials can be recycled perfectly. In 2005, 62Gt/yr materials have been processed, generating 41Gt of outputs, (19Gt biomass for feed, food and fodder, 12Gt fossil fuels, 4.5Gt mined ores) (UNEP, 2011). At the same time, only 4Gt of materials have been recycled. This is not surprising, since certain materials that are currently used cannot be recycled, such as fossil fuels and biomass burnt for energy.[38] One-fifth of total resources used worldwide are fossil fuels, and almost half are energy carriers. The 98% of fossil fuels that are burnt as a source of energy along with the biomass consumed for feed, food, and fodder cannot be re-used or recycled. Of course, shifting to a 100% renewable energy provision would solve this problem (although perhaps at the cost of creating others, Reason 2), but we are still far from this situation.

Another problem is that many modern products are too complex to be recycled. Miniaturisation can save material but renders the recovery of materials more difficult – and when this is technically feasible (which is not always the case), more costly and thus less economically interesting. Reuter et al. (2018) study the recyclability of one of the most modular smartphones (Fairphone 2) and find that the best possible recycling scenario would only recover about 30% of the materials. Most problematically, this is also the case for technology to harvest and store renewable energy. UNEP (2011) estimated that less than 1% of speciality metals are recycled.

A third point is that improvements in recycling are often more than cancelled out by rises in rates of replacement (sometimes fuelled by planned obsolescence). Indeed, if rates of recycling are increasing at a slower pace than the reduction of products' average lifetime (i.e. the rate of product replacement), then resource use is set to increase. If the ability to recycle is slower than the will to produce, then virgin resources will have to be used.

There is not enough waste to recycle

This last argument is a matter of basic arithmetic. Just for now, let us still assume that rates of recycling would increase significantly faster than their current trends (while still relaxing the assumption that recycling in itself requires energy and new materials). Yet, even this would in itself not be a guarantee

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[38] This is also the case for dispersive uses that divert materials from recycling circuits (e.g. scarce metals used in ink and paint pigments, additives in glass and plastic).

to maintain the growing economy's throughput, since in an economy with increasing resource use, the amount of used material that can be recycled will always be smaller than the material needed for growth. As the economy keeps on expanding, more materials will be required than the ones available from previous periods, and so the materials available for recycling within this economy will not suffice. This would be like a snake trying to make a larger skin out of the scraps of its previous, smaller skin.

As shown by Grosse (2010), in an economy where material consumption increases, recycling can only delay resource depletion. The author takes the example of steel, the best-recycled material worldwide. At a current 62% recycling rate and with a yearly rise in consumption of 3.5%, recycling is only delaying depletion by 12 years. If we keep consumption rates steady, even increasing recycling rates to 90% would only add an extra seven years before depletion.

Arnsperger and Bourg (2017, p. 73) apply the Grosse (2010) calculation to copper. They assume that the residence time of copper in the economy is of 40 years and that 60% of it can be recycled with current technologies. Out of the 6 million tons of copper used in 1975, this means that 4 million could have been recovered by 2015. However, consumption of copper has grown to 16 million in the last 40 years and so, despite recycling, 12 million tons of virgin copper must still be extracted. In this case, even with assuming an illusory 100% recycling rate, the extraction would have more than doubled during the period.

What exacerbates the limited availability of products to be recycled is the fact that a significant portion of all resources used ends up in infrastructure, often for quite some time. De Decker (2018) proposes a simple back-of-the-envelope calculation. In 2005, the world used 62Gt of natural resources: 4Gt for disposable products lasting less than one year and 26Gt in buildings, infrastructure, and consumer goods lasting more than one year. The same year, 9Gt of resources were disposed of in the process of production. The author concludes that the total quantity of materials available for recycling at the start of the second year of production is 13Gt (4Gt of disposable products + 9Gt of surplus resources), of which only a third could be effectively recycled. Plain to see that this number is not only short of what would be needed just to produce the same as in the previous year (62Gt) but even more so for a growing economy.

An infinitely growing circular economy is an arithmetical impossibility, and a contradiction in terms. Recycling is itself limited in its ability to provide resources for an expanding material economy. In the end, our point is not to question the usefulness or relevance of recycling, which could on the contrary play a crucial role in a non-growing economy, but merely to point to the fact that hopes of decoupling based on recycling are misinformed. The reality is that recycling rates are currently low and only slowly increasing, that recycling processes generally still require a significant amount of energy and virgin raw materials, and that it is mathematically impossible for recycling to match rates of replacement in a context of increasing consumption.

6. Insufficient and inappropriate technological change

The debate on the likeliness of future decoupling is, at its very core, a debate on the potential of technological innovation. Decoupling may have not occurred yet, and economic growth may seem biophysically constrained, either because of rising costs of extraction (Reason 1), unforeseen problem shifting (Reason 3), material infrastructure (Reason 4), or limited recycling (Reason 5), but the green growth discourse develops on the assumption that future innovations soon to come would do away with that. In our opinion, this hypothetical argument has several shortcomings having to do with the purpose, unintended consequences, and pace of technological change. Simply put, technological progress is (1) not targeting the factors of production that matter for ecological sustainability and not leading to the type of innovations that reduce environmental pressures; (2) it is not disruptive enough as it fails to displace other undesirable technologies; and (3) it is not in itself fast enough to enable a decoupling that is absolute, global, permanent, large and fast enough. Essentially we are not arguing against innovation in itself. Our point is that technological innovation is most often ambivalent when it comes to addressing environmental issues and that the potential of future technological innovations is most likely too limited, and in any case uncertain. Relying on the belief that technological innovation will bring all necessary solutions to environmental problems appears as an extremely risky and unreasonable bet.

Not leading to relevant innovations

Innovation is not in and of itself a good thing for ecological sustainability. The desirable type of innovation is *eco-innovation* or one that results “in a reduction of environmental risk, pollution and other negative impacts of resources use compared to relevant alternatives” (Kemp and Pearson, 2008, p.5). But this is only one type among several. In general, firms have an incentive to innovate to economise on the most expensive factors of production to maximise profits. Because labour and capital are usually relatively more expensive than natural resources, more technological progress will likely continue to be directed towards labour- and capital-saving innovations, with limited benefits, if any, for resource productivity and a potential rise in absolute impacts due to more production. But decoupling will not occur if technological innovations contribute to saving labour and capital while leaving resource use and environmental degradation unchanged.

Another issue is that technologies do not only solve environmental problems but also tend to create new ones. Assuming that resource productivity becomes a priority over labour and capital productivity, there is still nothing preventing technological innovations from creating more damage. For example, research into processes of extractions can lead to better ways to locate resources (imaging technologies and data analytics), to extract them (horizontal drilling, hydraulic fracturing, and automated drilling operations), and to transport them (Arctic shipping routes). These innovations may target resource use but with a result opposite to the objective of decoupling, that is more extraction. And this is not even considering unintended side-effects, which often accompany the development of new technologies (Grunwald, 2018).

Not disruptive enough

Another problem has to do with the replacement of harmful technologies. Indeed, it is not enough for new technologies to emerge (innovation), they must also come to replace the old ones in a process of “exnovation” (Kimberly, 1981). What is required is a “push and pull strategy” (Rockström et al., 2017): pushing environmentally-friendly technologies into society and pulling harmful ones, like fossil-based infrastructure, out of it.

First, in reality, such a process is slow and difficult to trigger. Most polluting infrastructures (power plants, buildings and city structures, transport systems) require large investments, which then creates inertia and lock-in (Antal and van den Bergh, 2014, p. 3). Let us, for instance, consider the energy, buildings, and transport sectors, which account for the large majority of world energy consumption and greenhouse gas emissions. Initial lifetime for a nuclear or a coal power plant is about 40 years. Buildings can last at least as much. The average lifetime for a car is 12-15 years, and this is about what it takes for an innovation to spread in the vehicle fleet. The wide availability of petrol refuelling stations gives an infrastructural advantage to petrol-based cars, whereas this is the opposite situation for electric, gas, or hydrogen vehicles that would require different and new supporting infrastructures. Building a highway or a nuclear plant is a commitment to emit for at least as long as these infrastructures will last – Davis and Socolow (2014) speak of “committed emissions.”

Energy is a good case in point: using more renewable energy is not the same as using less fossil fuels. The history of energy use is not one of substitutions but rather of successive additions of new sources of energy. As new energy sources are discovered, developed, and deployed, the old sources do not decline, instead, total energy use grows with additional layers on the energy mix cake. York (2012) finds that each unit of energy use from non-fossil fuel sources displaced less than one-quarter of a unit of its fossil-fuel counterpart, showing empirical support for the claim that expanding renewable energies is far from enough to curb fossil fuel consumption. The relative part of coal in the global energy mix has been reduced since the advent of petroleum but this occurred in spite of absolute growth in the use of coal (Krausmann et al., 2009).

Moreover, even if the decision to substitute renewables to all fossil energies was enacted, it is doubtful whether this process can happen fast enough – or even at all, considering material requirements into consideration. In a recent study, the International Renewable Energy Association (IRENA, 2018) estimates that a continued GDP growth compatible with a 2°C warming target would require the addition of 12,200 GW of solar and wind capacity by 2050. This means increasing renewable capacity addition rates by 2.3 to 4.6 times. Because the study assumes a parallel decrease in energy intensity of 2.8% per year (double the historical rate), and because it aims for the 2°C target (and not the more ambitious 1.5°C), one might consider that the speed of renewable energy development would need to be even higher. For instance, Garrett (2012) calculates that one would need to build one nuclear power plant per day (or equivalent in renewables) in order to decarbonise an energy demand steadily growing at current rates.

This pattern observed with energy, whereby new technologies supplement rather than replace existing ones, can be observed in many other sectors as well. Computers have not brought about the paperless office because computers and papers came to complement each other (York, 2006). The rise of synthetic rubber, whose production was established during World War II, did not stop natural rubber production and consumption from increasing steadily throughout the 20th century (Cornish, 2001). Likewise, the explosion of synthetic fibers like polyester and nylon has not displaced natural fiber production. While yearly world production of synthetic fibers has grown from less than 2 Mt in 1950 to above 60 Mt today, the production of natural fibers has more than tripled, from under 10 to roughly 30 Mt, with annual variations due to climatic conditions (The Fiber Year, 2016). Additional consumption largely surpassed substitution.

Not fast enough

In light of the past decades of technological change, the rate of improvement that is needed for high-income, high-footprint economies to absolutely decouple appears disproportionate in contrast to past and present rates of technical progress.

Let us consider the example of carbon emissions. Jackson (2016, pp. 96–100) considers several simple hypothetical decoupling scenarios. The first baseline scenario runs as follow: extending the trend of global annual per capita economic growth of 1.3% in parallel of 0.8% of expected annual population growth and with the average annual decline of carbon intensity of 0.6%, that has been observed since 1990, would result in carbon emissions growing by 1.5% per year (1.3% + 0.8% – 0.6% = 1.5). In order to achieve a 90% emission reduction in 2050 compared to current levels with the same GDP and demographic hypotheses, the emission intensity would need to decline at an average rate 8% per year until 2050 – reducing the average carbon content of economic output to 20 gCO_2/US$, that is to say 1/26 of what it is today (497 gCO_2/US$). In comparison, the carbon intensity of the global economy fell from about 760 gCO_2/US$ in 1965 to just under 500 g/CO_2/US$ in 2015, that is to say, an annual decline of only 1%.

Many more ambitious scenarios can be imagined,[39] but the message is already clear: relying only on technology to mitigate climate change implies extreme rates of eco-innovation improvements, which current trends are very far from matching, and which, to our knowledge, have never been witnessed in the history of our species. Such an acceleration of technological progress appears highly unlikely, especially when considering the following elements:

First, global carbon intensity improvement has been slowing down since the turn of the century, from an average yearly 1.28% between 1960 and 2000 to 0% between 2000 and 2014 (Hickel and Kallis, 2019, pp. 8–9). Narrowing the scope to high-income OECD countries only, where most innovations are developed, the improvement rate of CO_2 intensity still declines from 1.91% (1970-2000) to 1.61% (2000-2014), which is a long way from matching appropriate levels to curb emissions to a 2°C target, let alone to 1.5°C.

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[39] Since in the aforementioned baseline scenario, the carbon budget ends up being fully used by 2025, the author calculates in a second scenario the requirement for a 95% reduction holding all else equal. The rate of improvement rises to a 10.4% reduction in carbon intensity year on year, but the carbon budget still runs out by the end of the 2020s. To avoid this, a third scenario sets the target year to 2035 instead of 2050, and the necessary speed of technological change becomes 13% for a 90% reduction and 15% for a 95% reduction. In scenario 4, low-income countries are expected to match the income of the richer ones (with a 2% expansion in rich countries, it will take a rate of growth of 7.6% in poor ones for both levels of income to converge). Under those conditions, the carbon intensity must be less than 2 gCO2/$ to achieve a 95% reduction, almost 1/250 of what it is today. Meeting these targets by 2035 requires a reduction of carbon intensity to average an annual 18%, 100 times faster than the current rate of change.

This empirical observation is nothing like a surprise with regards to the theory. Technological innovation is limited as a long-term solution to sustainability issues because it itself exhibits diminishing returns (Reason 1). Tracking the number of utility patents per inventor in the US over the 1970-2005 period, Strumsky et al. (2010) provide evidence that the productivity of invention declines over time, including in the sectors such as solar and wind power as well as information technologies (which are often acclaimed for their innovative potentials). “Early work [...] solves questions that are inexpensive but broadly applicable. [Then] questions that are increasingly narrow and intractable. Research grows increasingly complex and costly [...]” (ibid. 506). Looking at total factor productivity changes from 1750 to 2015, Bonaiuti (2018) argues that humanity has entered an overall phase of decreasing marginal returns to innovation.

To sum up, technology is no panacea. It is indeed impossible to predict what the future holds in terms of innovations over the long term. Yet, the point is, that reasons to be sceptical about the potential for technological change to foster the type of decoupling we described as necessary are multiple and serious. First, many technologies that could have severed part of the link between GDP and environmental pressures have been here for several decades now with only minimal effects. More importantly, all innovations do not go in the direction of more ecological sustainability. In a capitalist and growth-oriented economy, innovation is most often strongly dependent on profit-making opportunities, hence partly oriented to this aim. In such a context, most innovations may result in GDP increase but only a few of them might help mitigate environmental pressures. Future technological changes may perhaps bring some additional improvements, provided these are not cancelled by rebound effects (cf. Reason 2) and provided they do not result in problem shifting (cf. Reason 3). Past and current paces of technological evolutions are clearly at odds with the urgent and radical changes that the environmental crises call for and declining marginal rates of improvement (cf. Reason 1) give little reason for optimism about the future.

7. Cost shifting

The absolute decoupling shown in early-industrialised nations is only apparent if those countries outsource their biophysically-intensive production somewhere else. This leakage effect[40] – also sometimes called “decoupling through burden shifting” (UNEP, 2014a) or “virtual decoupling” (Moreau and Vuille, 2018) can be either intentional or conjectural (Peters, 2008). It is intentional or direct when the geographical shift in production results from an obvious choice to relocate to jurisdictions with less stringent environmental regulations – this is referred to as the “pollution heaven hypothesis.” It is conjectural or indirect when the effect is attributed to a broader set of factors (e.g. differences in cost of labour, industrial capacity, access to resources, or technology). Based on this premise, globalisation would cause polluting activities to concentrate in the least regulated – most often low-income countries. Put another way, trade would enable the decoupling of certain regions at the expense of an intensification of environmental pressures elsewhere, or in other words, would allow high-consumption countries to externalise the environmental costs of production to low-consumption countries (one then speaks of “embodied” impacts, e.g. embodied emissions, embodied energy).

Empirical evidence of environmental cost shifting

The empirical literature on the embodied environmental pressures in trade is consistent. Reviewing embodied carbon studies, Sato (2014) identified a large and growing volume of embodied carbon emissions in international trade, which accounted in 2006 for around one-fourth of global emissions. Looking at 113 countries, Peters et al. (2011) find that the net emission transfers via international trade from low-income to high-income countries has quadrupled between 1990 and 2008.

This does not only concern emissions but also resources. In between 1997 and 2001, 16% of the global water footprint was embodied in global trade (Hoekstra and Chapagain, 2007). Raw material embodied in international trade accounted for 30% of the global material consumption increase during the 1990-2010 period, “this effect being due to the growing contribution of less material-efficient economies to global production” (Plank et al., 2018, p. 19). Likewise, Schandl et al. (2018, p. 8) report that global material efficiency is declining because of a “large shift of economic activity from very material-efficient economies, such as Japan, the Republic of Korea, and Europe, to the currently much less material-efficient economies of China, India, and Southeast Asia.”

For example, a 2011 OECD report claimed that Germany, Canada, Italy, and Japan had achieved an absolute decoupling of material consumption since the 1980 (OECD, 2011). Even though, as pointed out by Bednik (2016, p. 107), the authors of the report pinpoint that “parts” of this decoupling is due to the exportation of manufacturing activities in emerging and developing countries (OECD, 2011, pp. 15–16). The difference between the gross resource use (measured with a production approach) and

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[40] Because mostly focusing on carbon, this phenomenon is referred to as “carbon leakage” in the empirical literature. The term “leakage” depoliticises the process and so we prefer, following Kapp (1950) and the school of world-system analysis (most notably Hornborg, e.g. 1998) to call it a process of environmental cost shifting whereby richer nations systematically impose the environmental costs of their consumption onto poorer countries.

net resource use (measured with a consumption approach) was of 27.7% for Germany and 24.7% for Italy in 2004, and as high as 44% for France (Laurent, 2012).

More generally, Davis and Caldeira (2010) estimate the difference between production and consumption emissions to be around 30% in rich countries. When compared to the rates of supposedly absolute decoupling announced in certain studies, the sole factor of cost shifting is enough to explain the observation.[41]

Why does cost shifting happen?

What is observed empirically finds its theoretical explanation in world-system analysis and dependency theory (Amin, 1976; Emmanuel, 1972; Wallerstein, 1974). Building on such tradition, Hornborg (1998, p. 38) calls this process "ecologically unequal exchange": "a relation of exchange, even when it has been entered voluntarily, can generate a systematic deterioration of one party's resources, independence, and development potential." From this particular perspective, the world can be divided into core countries, semi-periphery countries, and periphery countries, with the former having more power to import wealth from and export ill to others.

Emmanuel (1972) showed how differences in the price of labour between nations lead to a net transfer of embodied labour from the poorest to the richest. What is relevant for decoupling is that the same mechanism is at work but with material, energy, and pollutions. If it is cheaper to produce what is most polluting elsewhere, and as a consequence, there will be a net transfer of environmental burden from the global North to the global South. In decoupling terms, this would mean that *core* countries find themselves in a situation of ecological deficit with their *periphery*.

Decoupling in certain regions of the world would be a "local illusion" (Hornborg, 2016, p. 115) or "geographical illusion" (Fischer-Kowalski and Amann, 2001) that is enabled by a process of

"environmental load displacement" (Muradian et al., 2001) or "cost shifting" (Kapp, 1950) from one locality to another or from the present to the future. Following this line of thinking, Hornborg (2001, p. 33) invites us to "think of the world as a system, in which one country's environmental problems may be the flip side of another country's growth." This is especially relevant when it comes to technological change. Hornborg (2019, p. 15) argues that modern technology "should be understood not simply as an index of ingenuity, but as a social strategy of appropriation (of labour and land)" or as "a strategy of displacement (of work and environmental loads)." A vacuum-cleaner may save time in cleaning the house, but it does so at the expense of someone having to spend time and energy building the vacuum, and a lot of more people having to extract the materials necessary for it.

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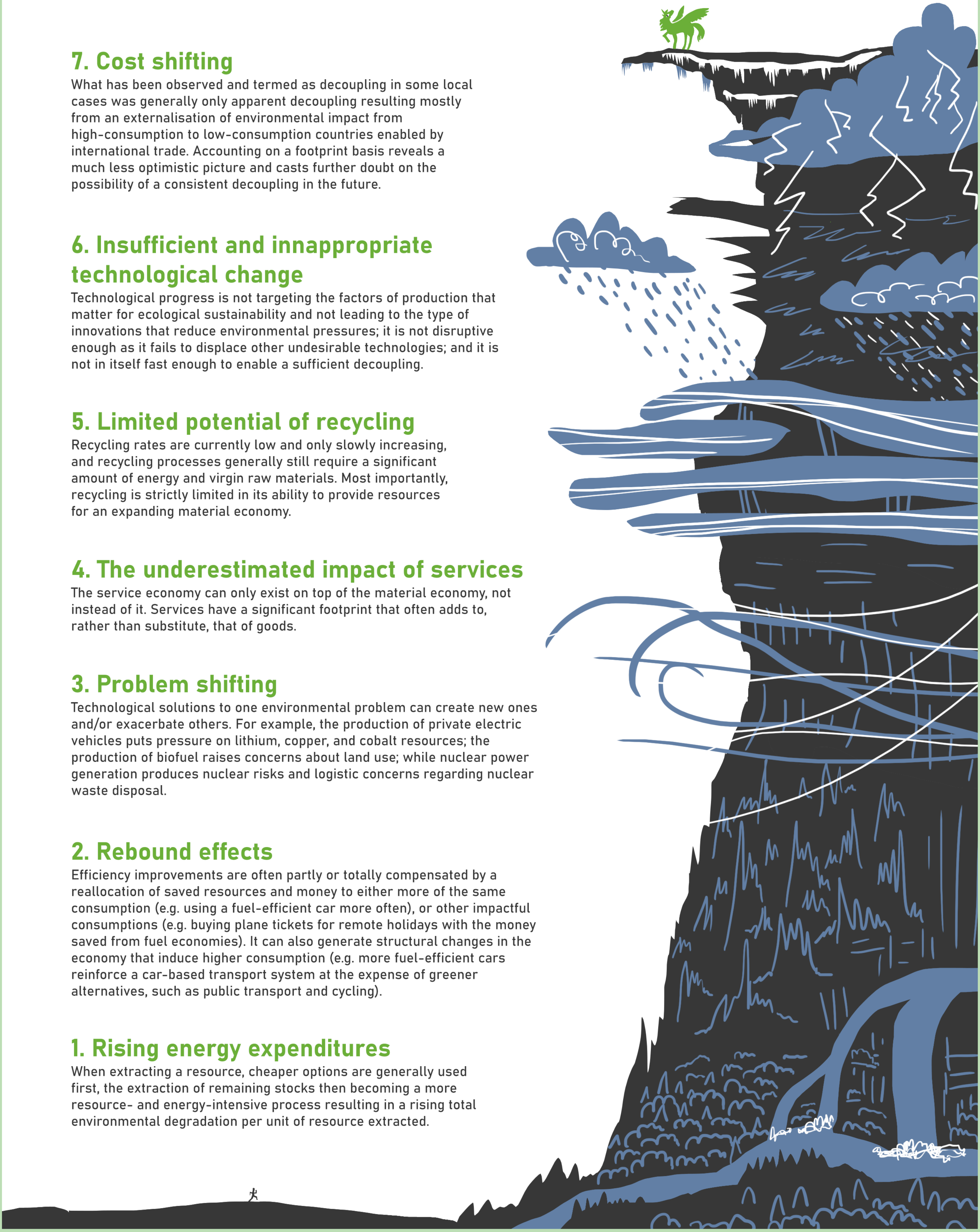
[41] In their study of embodied emissions in British imports, Druckman et al. (2008, p. 594) conclude that "any progress towards the UK's carbon reduction targets (visible under a production perspective) disappears completely when viewed from a consumption perspective."

It would be irrelevant to celebrate decoupling in one country if this one is achieved at the expense of coupling in another one, especially if the latter one is poorer than the former. There are strong theoretical reasons to believe that the few cases of local decoupling that are celebrated (which remain exceptions) are mostly a displacement of environmental pressures elsewhere, as we have shown in Section 2. If that is so, it means that ecological sustainability can only be achieved via a downscaling of polluting production. This reason is perhaps the most problematic of all. As long as individuals, firms, and nations stay engaged in cost-competition, there will be incentives to swipe ecological costs under the rug, with the lightening of footprints remaining a mere statistical trick.

Conclusions for Section 3

In this section we have offered a number of reasons to be sceptical about decoupling: (1) Rising energy expenditures, (2) rebound effects, (3) problem shifting, (4) the underestimated impact of services, (5) the limited potential of recycling in a growing economy, (6) insufficient and inappropriate technological change, and (7) cost shifting. Each of them taken individually casts doubt on the possibility for decoupling and thus the feasibility of "green growth." Considered all together, the decoupling hypothesis appears highly compromised, if not clearly unrealistic. It is urgent to draw the consequences in terms of policy making, and following the precautionary principle, to move away from the continuous pursuit of economic growth in high-consumption countries, in particular in the EU. Following the arguments we have discussed in this section, the burden of proof rests on decoupling advocates. Unless adequate and convincing demonstrations are brought against each and all of the above-mentioned arguments, the concept of decoupling remains an act of pure belief with little relevance for policy making.

7 barriers to green growth



7. Cost shifting

What has been observed and termed as decoupling in some local cases was generally only apparent decoupling resulting mostly from an externalisation of environmental impact from high-consumption to low-consumption countries enabled by international trade. Accounting on a footprint basis reveals a much less optimistic picture and casts further doubt on the possibility of a consistent decoupling in the future.

6. Insufficient and innappropriate technological change

Technological progress is not targeting the factors of production that matter for ecological sustainability and not leading to the type of innovations that reduce environmental pressures; it is not disruptive enough as it fails to displace other undesirable technologies; and it is not in itself fast enough to enable a sufficient decoupling.

5. Limited potential of recycling

Recycling rates are currently low and only slowly increasing, and recycling processes generally still require a significant amount of energy and virgin raw materials. Most importantly, recycling is strictly limited in its ability to provide resources for an expanding material economy.

4. The underestimated impact of services

The service economy can only exist on top of the material economy, not instead of it. Services have a significant footprint that often adds to, rather than substitute, that of goods.

3. Problem shifting

Technological solutions to one environmental problem can create new ones and/or exacerbate others. For example, the production of private electric vehicles puts pressure on lithium, copper, and cobalt resources; the production of biofuel raises concerns about land use; while nuclear power generation produces nuclear risks and logistic concerns regarding nuclear waste disposal.

2. Rebound effects

Efficiency improvements are often partly or totally compensated by a reallocation of saved resources and money to either more of the same consumption (e.g. using a fuel-efficient car more often), or other impactful consumptions (e.g. buying plane tickets for remote holidays with the money saved from fuel economies). It can also generate structural changes in the economy that induce higher consumption (e.g. more fuel-efficient cars reinforce a car-based transport system at the expense of greener alternatives, such as public transport and cycling).

1. Rising energy expenditures

When extracting a resource, cheaper options are generally used first, the extraction of remaining stocks then becoming a more resource- and energy-intensive process resulting in a rising total environmental degradation per unit of resource extracted.

Conclusions: Farewell to green growth

This report has sought to make a number of points. To begin with, scientific studies and political discussions about decoupling must be precise as to how they define the term (is it *relative* or *absolute*, dealing with *resource use* or *impacts*, *global* or *local*, and *temporary* or *permanent*?) and how it relates to existing environmental thresholds and political targets: Is it *sufficient* to achieve the target? Does it account for a *fair* distribution of burdens and benefits?

In the second section, we have reviewed the empirical decoupling literature searching for evidence of the type of decoupling that would justify green growth as a political strategy. Our finding is clear: the decoupling literature is a haystack without a needle. Of all the studies reviewed, we have found no trace that would warrant the hopes currently invested into the decoupling strategy. Overall, the idea that green growth can effectively address the ongoing environmental crises is insufficiently supported by empirical foundations.

Here, it is important to note that decoupling is neither a new nor a never-tried strategy. It has been the main sustainability plan, at least for the OECD and the European Commission, since 2001, and a key feature of many member states' environmental and industrial policies since the 1990s. Decoupling is not an innovative strategy but rather the continuation of what has been done in the European Union in the last decades. The meagre achievements of the decoupling strategy until now reported in Section 2 cast serious doubt as to whether prospects for the short- to medium-term future are better. Considering the last two decades as a trial period, one must confront the fact that decoupling has failed to deliver the ecological sustainability it promised

At last, we claimed that there were several reasons to be sceptical about the occurrence of decoupling in the future. (1) Rising energy expenditure, (2) rebound effects, (3) problem shifting, (4) the underestimated impact of services, (5) limited potential of recycling, (6) insufficient and inappropriate technological progress, and (7) cost shifting can, each individually, and even more all together, compromise or even dismiss the possibility of “green growth.” The insight here is not that efficiency improvements are unnecessary (and in that sense, we support most of the decoupling-targeted policies advocated by UNEP in their 2014a report), but instead that it is theoretically and empirically unrealistic to expect those to absolutely, globally, and permanently delink a constantly growing economic metabolism from its biophysical base. Given the historical correlation of GDP and environmental pressures as well as the required technological improvements needed for a sufficiently large and fast reduction in resource use and environmental degradation, relying on decoupling alone to solve environmental problems appears to be an extremely risky and irresponsible bet. Framing issues of social-ecological justice with the concept of decoupling is like trying to cut a tree with a spoon: it is likely to be a long attempt and most likely to fail in the end.

As Daly (1977, p. 115) already argued 40 years ago, the bet we are facing is similar to Pascal’s Wager. Either we hope that somehow these seven problems will solve themselves, continue growth-as-usual and risk a social and environmental collapse; or we acknowledge that decoupling is likely to fail with irreversible consequences on the environment, and follow a precautionary principle approach, moving away from a risky green growth strategy and directly reducing the problematic forms of production and consumption today. In light of what this report shows, prudence alone warrants the abandonment of decoupling and green growth as a sole strategy for sustainability.

Because extraordinary claims require extraordinary evidence, the burden of proof should fall upon advocates of decoupling. As we have argued in Section 3, any claim for decoupling must address a series of arguments. This is the challenge for any policy attempting to follow the IPCC 1.5°C mitigation scenario and implement the Sustainable Development Goals. So far, the green growth literature on the topic is either silent or unconvincing regarding any of these seven arguments we have listed in this report. Reflecting on these findings, our recommendation is the following: policymaker have to acknowledge the fact that addressing the climate and biodiversity crises (which are only two of several environmental crises) may require a direct downscaling of economic production and consumption in the wealthiest countries. In other words, we advocate a shift in priorities from *efficiency* to *sufficiency*, with the latter being put before the former. The decoupling strategy takes consumption levels as granted and relies on the hope that further economic growth will provide the means to (over) compensate for its own environmental impacts. It is indeed an appealing approach to policymakers in that it requires only minimal changes in economic and social structure. However, this focus on supply appears counter-intuitive and now outdated. The obsession with decoupling in European politics shows a problematic lack of political creativity and ambition, as well as an inability from policymakers to imagine the economy differently than in its current form.

The problem is that, even if decoupling could be definitely proven impossible, it will take some time for this to be demonstrated to the satisfaction of its proponents. As argued by Fletcher and Rammel (2017), decoupling acts as a distracting fantasy that warrants a (continuously more) destructive path with both the promise of success and demonstration of its impossibility deferred into the future. But as decoupling fails to materialise, natural resources deplete and ecosystems collapse. In that sense, decoupling is not an opportunity but a threat. Ultimately, until GDP is actually decoupled from environmental pressures, any additional production will require a larger effort in reductions of resource and impact intensity to stay away from resource conflicts and ecological breakdown. In that sense, trying to reduce impacts while growing makes as little sense as trying to brake while accelerating in front of an obstacle.

The least impactful production and consumption is the one that does not occur. In one of their decoupling reports, UNEP (2014a, p. 48) spends a full page describing all possible technologies to improve trucking fuel efficiency, from full roof deflectors, sloped hoods and aero bumpers, to curved windshields. Options they do not mention include simply reducing the speed of these trucks or substituting rail transport to freight by trucks, or even more effective, reducing the need for freight altogether by relocalising production and consumption. The fact that such common-sense solutions are not even considered in a comprehensive report focused on policy options is telling evidence of how dominant the unidimensional emphasis on eco-efficiency has become.

In contrast to hydrogen cars, region-wide smart-grids, and well-functioning carbon markets, reducing production and consumption is not an abstract narrative. In the last two decades, movements in the global North (transition towns, degrowth, eco-villages, slow cities, social and solidarity economies, economies for the common good) have started to become organised around the concept of sufficiency, which could inspire a cross-cutting policy approach. What they say is that more is not always better and that in a climate-constrained world, enough can be plenty. As argued by many of these actors, the choice of sufficiency is not one of sacrifice, unemployment, rising inequality, poverty, and shrinking welfare States. Instead, it is the choice of a fair economy that remains within the carrying capacities of the biosphere or, as the EU 7th Environmental Action Programme has called it, “living well within the planet’s ecological limits.” Listening to these alternative options, we should reframe the debate altogether: what we need to decouple is not economic growth from environmental pressures but prosperity and the “good life” from economic growth.

This work highlights the need for a new conceptual toolbox to inform environmental policies. In this perspective, it appears urgent for policymakers to pay more attention to and support the existing diversity of alternatives to green growth. Drawing lessons from the diversity of people and frameworks engaged in imagining and enacting alternative ways of life is a promising way to solve what we perceive as a crisis of political imagination. The success of that initiative matters for what is at stake is nothing short of the future of our children and grandchildren if not to say the human civilisation as such.

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Appendix: Summary of empirical literature

Variable	Author(s)	Year	Not an explicit decoupling study	Consumption (c) or Production (p)-based	Period	Scale	Magnitude	Permanence
Materials	Behrens et al.	2007		-	1980-2002	Global	relative	permanent
	Bithas and Kalimeris	2018		p	1900-1945, 1950-2000	Global	relative	temporary
				-	1951-2009		no	-
	Fischer-Kowalski and Amann	2001		c	1975-1996	National	relative	temporary
	Krausmann et al.	2018		p	1945-2002	Global	relative	permanent
				-	2002-2015	Global	no	temporary
	Wang et al.	2018		c	1995-2013	Australia, Japan, US, India	relative	permanent
	Wiedmann et al.	2015		c	1990-2008	Global	no	-
	Bringezu	2015		c	2000-2050	Global	no	-
	Zhang et al.	2017		-	1985-2009	US (flow indicators)	absolute	permanent
				-	2000-2009	US (stock indicator)	relative	permanent
	Krausmann et al.	2009		p	1900-2005	Global	relative (material intensity)	permanent
	Gilijum et al.	2014	x	-	1997-2007	Global: Africa, Asia, Europe, Latin America, Oceania	-	-
	Jollands et al.	2004	x	-	1994/95-1997/98	National: Austria, Germany, Japan, Netherlands, UK, US	-	-
	West and Schandl	2013	x	cp	1970-2008	-	-	-
Energy	Kovacic et al.	2018		p	1995-2013	14 EU countries (EU15 excluding Luxembourg)	relative	permanent
	Luzzati and Orsini	2009		p	1971-2004	Global	no	-
	Moreau and Vuille	2018		cp	2000-2014	Switzerland	relative	permanent
	Szlavik and Sebestyen Szep	2017		-	1990-2015	Poland, Czech Republic, Slovakia, Hungary	both	temporary
	Wu et al.	2018		p	1965-1975	Brazil, Germany, France, UK, US	relative	both
				p	1976-1985	China, France, Germany, India, UK	relative	both
				p		US	absolute	temporary
				p	1986-1995	Brazil, China, France, Germany, UK, US	relative	both
				p	1996-2005	China, France, Germany, India, Russia, UK, US	relative	permanent
				p	2006-2015	Brazil, China, Germany, India, Russia	relative	-
				p		France, UK, US	absolute	-
	Feng et al.	2015		c	2007-2013	US	relative	both
	Cserklyei	2014		-	1971-2010	Multiregional, 99 countries	relative	temporary
	Semienuk	2018		-	1950-2014	Global	no	-
GHG	Cansino and Moreno	2018		p	2012-2013	Chile	relative	temporary
				-	1990–1991, 1999–2001, 2002–2003, 2004–2006, 2008–2010, 2012–2013		absolute	temporary
	Chen et al.	2018		cp	2001-2015	30 OECD countries	absolute	permanent

GHG	Cohen et al.	2018		p	1990-2014	Brazil, Mexico, Turkey, Korea, South Africa, Indonesia, India, China, Canada, Japan, Australia, US	relative	permanent
				p		Italy, Russia, Ukraine, France, Germany, UK	absolute	permanent
				c	1990-2014	Mexico, Korea, South Africa, Indonesia, India, China, Canada, Japan, USA, Ukraine, France, UK	relative	permanent
				c		Germany, Russia	absolute	permanent
	Jiang and Li	2017		p	1991-1993, 1995-1998, 1999-2001, 2002-2003, 2004-2005, 2006-2007, 2009-2010, 2012-2013	US	no	temporary
				p	all other years in the study period (1990-2014)		relative	temporary
	Jiborn et al.	2018		cp	1995-2009	Sweden, UK	relative	permanent
	Liddle and Messinis	2017		p	1870-2010	Australia, Canada, Ireland, Italy, Norway	relative	permanent
				p	1981/1981/1980-2010	Belgium, Netherlands, US	absolute	permanent
				p	1968/1980/1968/1972-2010	Denmark, France, Switzerland, UK	absolute	permanent
	Longhofer and Jorgenson	2017		p	1970-2009	Australia, Brazil, Canada, Denmark, Finland, France, Greece, Hungary, Ireland, Italy, Japan, Netherlands, Norway, Portugal, South Africa, Spain, Sweden, UK, US	relative	permanent
	Madaleno and Moutinho	2018		p	2000-2008, 2010-2013	EU-15	relative	temporary
				p	1996-1999	EU-15	absolute	temporary
	Marques et al.	2018		p	1965–1975	Australia	no	-
				p	1975-2016		relative	permanent
	Pilatowska and Wlodarczyk	2017		cp	1990-2012	Denmark, Sweden, Austria (since 2005), Belgium, France (since 2005), Germany	absolute	permanent
				p	2010-2012	Finland, Netherlands	relative	permanent
	Roinioti and Koroneos	2017		p	2003-2007, 2009-2010	Greece	relative	temporary
				p	2005-2006, 2007-2009		absolute	temporary
	Wang et al.	2018		P	2000-2001, 2006-2007,2011-2013	China	relative	temporary
				P	2000-2001, 2005-2006, 2010-2012	US	absolute	temporary
				P	2000-2014		absolute	permanent
				p	2001-2005, 2012-2014		relative	temporary
	Azomahou et al.	2006		p	1960-1996	Global (100 countries)	no	-
	Bassetti	2012		p	1970-2006	Global (126 countries)	no	-
	Fosten et al.	2012		p	1751-2007	UK	absolute	permanent
				p	1850-2002	UK	absolute	permanent
	Bertinelli and Strobl	2004		-	1950-1990	Global (122 countries (CO2) and 108 countries (sulfur)	no	-
	Jiang et al.	2016		-	2005-2006, 2010-11, 2011-12	US	absolute	temporary
	Itkonen	2012		-			no	-
	Knight and Schor	2014		-	1991-2008	29 high-income countries	no	-

	Lean and Smyth	2009		p	1980-2006	ASEAN countries: Indonesia, Malaysia, Philippines, Singapore and Thailand	absolute	permanent
	Lin et al.	2016		-	1980-2011	Kenya, Nigeria, Egypt, South Africa, DR Congo	no	-
	Huang et al.	2007		p	1990-2003	Annex II and EIT	absolute	-
	Azam and Khan	2016		p	1975-2014	China and US	no	-
	Azam and Khan	2016		p	1975-2014	Tanzania and Guatemala	absolute	temporary
	Tapio	2005		-	1990-2001	EU15 countries	absolute	temporary
				-	1990-2001	National: UK, Sweden and Finland	relative	temporary
	Wagner	2006		-	1986-1998	Global	no	-
	Akbostanci et al.	2009		p	1968-2003	Turkey	no	-
	Schröder and Storm	2018		c	1995-2011	61 countries	no	
				p	1995-2011	61 countries	relative	temporary
	Finel and Tapio	2012		c	1975-2005, special focus on 2000-2005	national (137 countries)	relative and absolute	temporary
	Wu et al.	2018		p	1965-2015	Brazil, China, France, Germany, India, UK, US, Russia	relative	permanent (except for India and Brazil)
Pollutants	Chang et al.	2018		p	1992-2014	Japan	absolute	permanent
	Selden and Song	1994		p	1973-75, 1979-84	Global	absolute	temporary
	Stern and Common	2001		p	1960-1990	Regional; OECD countries	absolute	-
	Diaz and Rosenberg	2008	x	-	2008	Global	-	-
	Bouwman et al.	2012	x	-	1900-2000 scenarios for the period 2000-2050	Global	-	-
	Billen et al.	2013	x	cp	1951-2005	Global	-	-
Waste	Jaligot and Chenal	2018		cp	1996-2015	Canton of Vaud in Switzerland	no	-
	Tsiamis et al.	2018		c	1998-2013	US	relative	permanent
Biodiversity	Mills and Waite	2009		p	1972-1992	National	no	-
	Asafu-Adjaye	2003		c	1990-1999	Global	no	-
	Raymond	2004		c	2002	National (140 nations)	no	-
	Mozumder et al.	2006		-	1998	National	no	-
	Dietz and Anger	2003		-	1950-1991 and 1999	Global (141 countries)	no	-
	Tevie et al.	2011		-	2007	US (48 states)	no	-
	Naidoo and Adamowicz	2001		-	1999	Global	absolute only for birds	temporary
	Koirala et al.	2011		cp	1992-2009	Global	no	-
	Ceballos et al.	2015	x	-	1500-2015	Global	-	-
	Butchart et al.	2012	x	-	1988-2008	Global	-	-
Ecological Footprint	Caviglia-Harris et al.	2009		p	1961-2000	Global	no	-
	Szigeti et al.	2017		c	1999 - 2009 (data only collected for the two years, not in between)	Global	both	-

Energy, Water, Land, (Air) **Energy, Pollutants** **Energy, Water, (Air)**	Conrad and Cassar	2014		p	1995-2012	Malta	relative	temporary
	Naqvi and Zwickl	2017		p	1995-2008	18 EU countries	both	both
	Van Caneghem et al.	2010		p	1995-2006	Flanders (climate change, acidification, photo-oxidant formation, human toxicity, freshwater aquatic ecotoxicity and eutrophication)	absolute	permanent
				p	1995-2006	Flanders (industrial waste generation, energy consumption)	relative	permanent
Energy, Materials	Ward et al.	2016		p	2015-2050	Australia	relative	temporary
	Schandl et al.	2016		cp	1990-2010	Global	relative	
GHG, Energy, Materials,	Wood et al.	2018		cp	1995-2011	Global	absolute (land use)	permanent
Water	Wang et al.	2016		c	2007	Global (110 countries)	relative (domestic blue water use)	permanent
	Richey et al.	2015	x	cp	2013	Global	-	-
	Loch and Adamson	2015	x	cp	2011	Local (Australia's Murray–Darling Basin)	-	-
	Wada and Bierkens	2014	x	-	1960-2010	Global	-	-
	Oki, Yano, and Hansaki	2017	x	cp	2017	Global	-	-
	Strokal et al.	2019	x	-	2010	Regional (sub-basins of Europe, North America, South Asia)	-	-
	Zhao et al.	2015	x	cp	2007-2030	Regional: China		
	Hoekstra and Mekonnen	2016	x	c	1996-2005	Regional (UK)	-	-
	Ashaf et al.	2017	x	-	1997-2001, 1998-2007, 2000-2006	Regional (North America, Europe and the Middle East)	-	-
	Kiguchi	2015	x	c	2015 and scenarios for 2070	Global	-	-
Land use	Krausmann et al.	2013		p	1910-2005	Global	relative	permanent
	Bagliani	2008		-	2008	Global	no	-
	Tilman et al.	2011		cp	1961-2007	Global	relative (cropland)	-
	Kumar and Aggarwal	2003		p	1963-64 to 1995-96	Regional	relative (crop area)	temporary
	Kastner	2014		cp	1986-2009	Global (200 nations)	relative (cropland)	-
	Lambin and Meyfroidt	2010	x	-	1961-2010	Regional (China, Costa Rica, El Salvador, Vietnam)	-	-
	Weinzettel et al.	2013	x	-	2004	global	-	-
	Sandström	2017	x	cp	1986-2011	Regional (Finnland)	-	-
	Yu, Feng, Hubacek	2013	x	c	2007	Global (Australia, Brazil, Indonsia, India, Russian Federation, United Kingdom, Germany, Japan, China, US)	-	-
	Steen-Olsen et al.	2012	x	-	2004	regional (member states of the EU)	-	-
	Tukker et al	2016	x	-	2007	Global (43 countries)	-	-
	Schreinemachers et al.	2012	x	-	1990-2009	Global (except China)	-	-
	Borucke et al.	2013	x	-	2004	Global (200 countries)	-	-

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We would like to thank our funders

For the research work, the authors like to thank the following:

Timothée Parrique acknowledges funding received from the Marie Sklodowska Curie Fellowship Action in Excellent Research (grant agreement n° 675153).

Jonathan Barth acknowledges funding received by the KR Foundation.

François Briens thanks the French unemployment allowance scheme which made his contribution possible.

Christian Kerschner acknowledges funding received from the Czech science foundation under the project VE2NEX (GA CR 16-17978S).

Alejo Kraus-Polk acknowledges funding received from the California Department of Water Resources (grant agreement n° 4600012167).

For the production, layout, printing and dissemination, the **European Environmental Bureau**, **Deutscher Naturschutzring** and **Zoe Institute for Future-Fit Economies** would like to thank the following:

Federal Ministry
Republic of Austria
Sustainability and Tourism

This report has been produced with the financial assistance of the Federal Ministry of Sustainability and Tourism from the Republic of Austria. The contents of this report are the sole responsibility of the authors and can under no circumstances be taken as reflecting the position of the Austrian Ministry.

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KR foundation

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The European-wide project Make Europe Sustainable for All (MESA) is coordinated by the European Environmental Bureau (EEB) and implemented in 15 European countries by 25 partners. At the core of the project are various campaigns and advocacy activities. This report is part of the campaign on sustainable consumption and production (2019-2020). The contents of this report are the sole responsibility of the authors and can under no circumstances be taken as reflecting the position of all partner organisations.

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