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A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: bibliometric and conceptual mapping

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A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: bibliometric and conceptual mapping

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Social media abstract: How is decoupling of economic growth from resource use and emissions empirically investigated?

Abstract

As long as economic growth is a major political goal, decoupling growth from resource use and emissions is a prerequisite for a sustainable net-zero emissions future. However, empirical evidence for absolute decoupling, i.e., decreasing resource use and emissions at the required scale despite continued economic growth, is scarce and scattered across different research streams. In this two-part systematic review, we assess how and to what extent decoupling has been observed and what can be learnt for addressing the sustainability and climate crisis. Based on a transparent approach, we systematically identify and screen more than 11,500 scientific papers, eventually analyzing full texts of 835 empirical studies on the relationship between economic growth (GDP), resource use (materials and energy) and greenhouse gas emissions. Part I of the review examines how decoupling has been investigated across three research streams: energy, materials and energy, and emissions. Part II synthesizes the empirical evidence and policy implications (Haberl et al. part II, in review). In part I, we examine the topical, temporal and geographical scopes, methods of analysis, institutional networks and prevalent conceptual angles. We find that in this rapidly growing literature, the vast majority of studies – decomposition, 'causality' and Environmental Kuznets Curve analysis – approach the topic from a statistical-econometric point of view, while hardly acknowledging thermodynamic principles on the role of energy and materials for socio-economic activities. A potentially fundamental incompatibility between economic growth and systemic societal changes to address the climate crisis is rarely considered. We conclude that the existing wealth of empirical evidence merits braver conceptual advances than we have seen thus far. Future work should focus on comprehensive multi-indicator long-term analyses, conceptually grounded on the fundamental biophysical basis of socio-economic activities, incorporating the role of global supply chains as well as the wider societal role and preconditions of economic growth.

Keywords: Decoupling; Green growth; Degrowth; Environmental Kuznets Curve; Dematerialization; Decarbonization; Socio-Economic Metabolism

1) Introduction

Global resource use and greenhouse gas emissions are steadily increasing, driving the transgression of Planetary Boundaries and accelerating the anthropogenic climate crisis (IPCC 2018, Steffen *et al* 2015, Krausmann *et al* 2018, UNEP-IRP 2019, OECD/IEA 2018). These developments occur in lockstep with global economic growth and the rise of mass production and consumption (Krausmann *et al* 2018, UNEP-IRP 2019, OECD/IEA 2018). Making economic growth more 'inclusive and sustainable' is its own Sustainable Development Goal (SDG Nr. 8). However, perspectives on feasibility and required political strategies differ widely, depending on one's underlying conceptual angle on the relationship between economic growth and the environment. These range from the idea of an Environmental Kuznets Curve (Carson 2010) to greening growth through efficiency and decoupling (OECD 2011, UNEP 2011b, p 2011, World Bank 2012). Alternatively, calls for degrowth and post-growth approaches are voiced (van den Bergh and Kallis 2012). As long as economic growth persists as a dominant political goal, decoupling economic growth from resource use and emissions is a prerequisite for a sustainable net-zero carbon emissions future.

On political and research agendas, improving resource and energy efficiency appear as main strategy for decoupling economic growth from environmental pressures and impacts (UNEP 2016, UNEP-IRP 2019, OECD 2019). In the conceptualization of decoupling, resource decoupling and (environmental) impact decoupling are distinguished (UNEP 2011a). Resource decoupling refers to the relationship between GDP and biophysical resource use (materials, energy, etc.), whereas impact decoupling refers to the reduction of environmental impacts per unit of GDP (e.g. emissions from energy use and land-use changes). This difference brings quite different mitigation strategies into view, for example reducing fossil fuel use versus carbon capture and sequestration (CCS) or solar geo-engineering (IPCC 2018). Also, what is neatly summarized into resource use versus impacts is much more complex, as different resources have a multitude of environmental impacts, making aggregate proxy indicators indispensable (UNEP-IRP 2019).

To understand if decoupling occurs at the scale required to address the sustainability and climate crisis, a broad systemic viewpoint on the interdependencies between energy, materials and emissions therefore becomes necessary, which is sometimes called the "resource nexus" (Bleischwitz *et al* 2018). We operationalize the issue through the concept of the socio-economic metabolism, which posits that to understand the biophysical basis of society, one needs to investigate the systemic relations between economic growth, resource use (energy and materials) and emissions, as embedded in a broader socioeconomic and political perspective(Haberl *et al* 2019, Pauliuk and Hertwich 2015). To understand the potentials for absolute decoupling at scale, a systemic analysis across indicators becomes necessary. We therefore focus on resource decoupling for energy and materials, with the aim of understanding potentials for emissions reductions (a form of impact decoupling). This is supported by the IPCC demonstrating that energy efficiency and demand-side measures entail less risks and offer a range of co-benefits to societies compared to technological fixes (Anderson and Peters 2016, Edenhofer *et al* 2014). We thereby contribute to a much needed renewed focus on demand-side solutions to climate change mitigation (Creutzig *et al* 2018, 2016).

1.1.) Existing reviews on resource use, emissions and economic growth

A number of reviews touched on aspects of the decoupling issue. Some focus on specific methodological approaches or conceptual angles, e.g. theorizing the energy-growth relation (Stern 2011), econometric 'causality' testing between energy and growth (Kalimeris *et al* 2014, Tiba and Omri 2017, Ozturk 2010), emissions and growth (Mardani *et al* 2019), the problematic and inconclusive evidence on the Environmental Kuznets Curve (Stern 2004, Carson 2010, Dinda 2004, Tiba and Omri 2017, Sarkodie and Strezov 2019), or the role of efficiency versus consumption growth for increasing energy use and emissions (Lenzen 2016). These reviews all support a fundamental relationship between resource use and emissions with economic growth, however they usually find either no convincing evidence for absolute decoupling at the required scale, or remain inconclusive.

Two recent efforts are much closer to the heart of the decoupling question, but both do not attempt to systematically review the literature but are focused on either global studies or recent works only. (Hickel and Kallis 2019) summarize recent global findings on energy, materials and energy as well as emissions decoupling, finding no signs for an absolute decoupling at nearly the scale required at the global level. Their assessment of the feasibility of reconciling green growth and efficiency with the need for absolute reductions of reducing resource use and emissions is pessimistic. Along these lines, a recent report by the European Environmental Bureau (Parrique *et al* 2019) comprehensively summarizes the conceptual issues around decoupling and its limitations, and discusses recent empirical findings across a wide range of indicators. They also perceive a fundamental tension between economic growth and the need for absolute reductions of resource use and emissions required to mitigate the climate crisis and work towards sustainability. While these previous reviews provided important insights on the decoupling question, we think that our broader perspective based on a comprehensive and systematic bibliometric mapping of how decoupling has been investigated so far, can add important further insights on the robustness of this evidence base and the next steps.

1.3) Research scope and questions for this systematic review

This pair of review articles goes beyond previous reviews by using a systematic review procedure and comprehensively taking stock of the empirical approaches and evidence. We focus on analyzing the observed relationships between (1) economic growth, here approximated as GDP growth, and (2) resource use decoupling (materials, energy) as well as (3) impact decoupling for GHG emissions on the national to global scale. The two articles are based on state-of-the-art methods for systematically reviewing the peer-reviewed literature, ensuring the greatest possible extent of comprehensiveness and objectiveness. The present part I provides a bibliometric analysis of the empirical literature on decoupling to systematically understand the development of the relevant research streams, their conceptual and methodological approaches and limitations. Part II presents a qualitative and quantitative evidence synthesis to draw out insights regarding observed decoupling, the conditions thereof, and the strategic implications for policy. For the work presented in Part I, we specifically pose the following research questions:

1. How are the empirical interdependencies between economic growth and resource use and/or emissions investigated? How did the literature develop over time and what are the prevalent empirical, methodological and conceptual angles?
2. Which methodological and empirical insights on the robustness and insightfulness of the different approaches can be gained?
3. What are important next steps for the investigation of decoupling?

Part I of this review proceeds as follows: section 2 clarifies the scope and definitions used in the systematic review and summarizes all review procedures. Section 3 provides a bibliometric and conceptual mapping of the decoupling literature to shed light on the development of this literature and its underlying themes over time. Section 4 then critically discusses the research streams to uncover their potential contributions and limitations for the investigation of decoupling. These insights are then used in part II (Haberl *et al* in review, this issue) to partition the literature in thematic groups for analysis in terms of their substantive insights as well as their linkages to policies and strategies. Section 5 concludes on the status quo of the decoupling literature and makes some suggestions for the way forward.

2) Definitions, scope and methods used in the systematic review

In the following, we provide a concise summary of all definitions and methodological steps taken. We start by defining three research streams. The first research stream focuses on energy flows and energy conversion chains in socio-economic systems, utilizing energy statistics to quantify energy uses in terms of energy units (Joule, tons of oil equivalent, ...); this includes studies investigating exergy flows. The second research stream adds a more comprehensive perspective by asserting that materials and energy are necessarily interlinked and should be investigated jointly to understand the relationship between economic growth, resource efficiency and the resulting environmental pressures and impacts. Literature in this stream is mostly based on data obtained from material and energy flow analysis (MEFA), which harmonizes resource use data derived from various (inter)national databases (Fischer-Kowalski *et al* 2011, Krausmann *et al* 2017). Material and energy flows are measured in metric tons respectively Joules along 50-60 categories and are usually grouped into biomass, fossil energy carriers, non-metallic minerals and ores and metals. The third research stream specifically investigates the interdependence between GHG emissions and economic growth. We distinguish between studies limited to CO_2 emissions from fossil fuel combustion and industrial processes such as cement manufacture, and more comprehensive studies taking 'all' GHG emissions (CO_2, CH_4, N_2O and other GHGs) into account. The latter also cover emissions from agriculture and land use, land-use change and forestry (LULUCF).

Furthermore, to understand decoupling, a differentiation between "production-based" and "consumption-based" approaches is indispensable, as it takes the increasing role of global trade into account (Peters 2008, Wiedmann and Lenzen 2018, Haberl *et al* 2019, Steininger *et al* 2015, Peters *et al* 2012). Lately also a third perspective, income-based responsibility, has been proposed, although there is little literature available so far (Marques *et al* 2012, 2013, Steininger *et al* 2015). A production-based or territorial system boundary is the most common approach to investigating resource use and emissions occurring "within" a national economy; UNFCCC specifically uses "territorial" emissions accounting. The difference between territorial and production-based perspective is mainly how international bunkers, aviation and shipping are allocated. Due to increasing concerns about the role of international trade and the fragmentation of supply chains in shifting environmental burdens across countries, a consumption-based or "footprint" approach has been developed (Wiedmann and Lenzen 2018, Peters *et al* 2012). This consumption-based perspective considers the materials, energy or emission directly and indirectly associated with the final demand of a population in a country, no matter where extraction or emissions occur internationally. For our systematic review, we specifically probe for the uptake of production- and consumption-based perspectives and insights.

In summary, we operationalize our systematic review in the following manner: this review focuses on quantitative, empirical studies on economic growth and resource use decoupling (material and energy), as well as impact decoupling for GHG emissions; studies presenting scenarios, modelling exercises and theoretical/conceptual discussions were excluded. We limit our review to studies at national to global level; sub-national, regional or urban studies are excluded. Only studies using comprehensive indicators are included, covering primary energy, final energy, useful energy and exergy, materials and energy, as well as emissions; studies on sectors, e.g. housing or manufacturing, or on particular materials or energy carriers, e.g. metals or electricity, are excluded. These criteria as well as the categories used for characterizing methods and conceptual angles are summarized in Table 1.

Table 1: Criteria applied for mapping the body of literature. All criteria except 1b, 2a,b allowed yes/no distinctions; positives were marked. For 1b the respective country was noted, for 2a,b the respective years.

1. Geographic scope of the study (1a, 1c and 1d were mutually exclusive)	
National (one country)	1a
If national, which country	1b
International (more than 1 country, but less than global)	1c
Global (sufficiently large sample to draw global conclusions, or global totals)	1d
2. Temporal scope of the analysis	
Starting year	2a
End year	2b
3. Type of resource or emission indicator(s)	
Production-based territorial indicator (e.g. GHG emissions in UNFCCC reports)	3a
Consumption-based footprint indicator (e.g. material footprint, carbon footprint)	3b
Material and energy flows (Domestic Material Consumption, Raw Material Consumption aka material footprint)	3c
Primary energy use (Total Primary Energy Supply (TPES) & TPES footprint)	3d
Final energy use (and final energy footprint)	3e
Exergy (useful exergy, useful energy, and the respective footprints)	3f
Fossil-fuel related and industrial (e.g. cement) CO2 emissions	3g
All/most GHG emissions (including N2O, CH4 and CO2 from LULUCF)	3h
4. Method of analysis	
Cross-sectional analysis (correlations across countries within the same year)	4a
Descriptive trend analysis (verbal interpretation of trends in energy intensity or related indicators)	4b
Regression and decomposition analysis (simple regression and decomposition analyses)	4c
Econometric time-series analysis (e.g. temporal correlations or panel analyses)	4d
Econometric causality tests (e.g. Granger causality tests)	4e
5. Conceptual angle (only if explicitly mentioned in title, abstract or keywords)	
Decoupling	5a
Green growth	5b
Degrowth	5c
Environmental Kuznets Curve	5d

Based on these considerations, we systematically reviewed the scientific literature in six steps (Figure 1), five of which are discussed in this article, whereas the last is presented in part II of this review (Haberl *et al* in review, this issue). Step 1, selection of relevant literature: we applied a search query to the Web of Knowledge and SCOPUS literature databases and pursued an expert solicitation for relevant articles, resulting in 11,511 studies. Steps 2-4: through duplicate removal and manual selection of relevant references in a screening and full-text coding phase, we reduced the number of articles to 835. Step 5, bibliometric literature mapping: we analyzed all selected references to identify temporal development of the literature, differing scopes and coverage as well as key conceptual angles (see Table 2 and Section 3). Step 6: the evidence synthesis and implications for policy and strategy are presented in part II (Haberl *et al* in review, this issue).

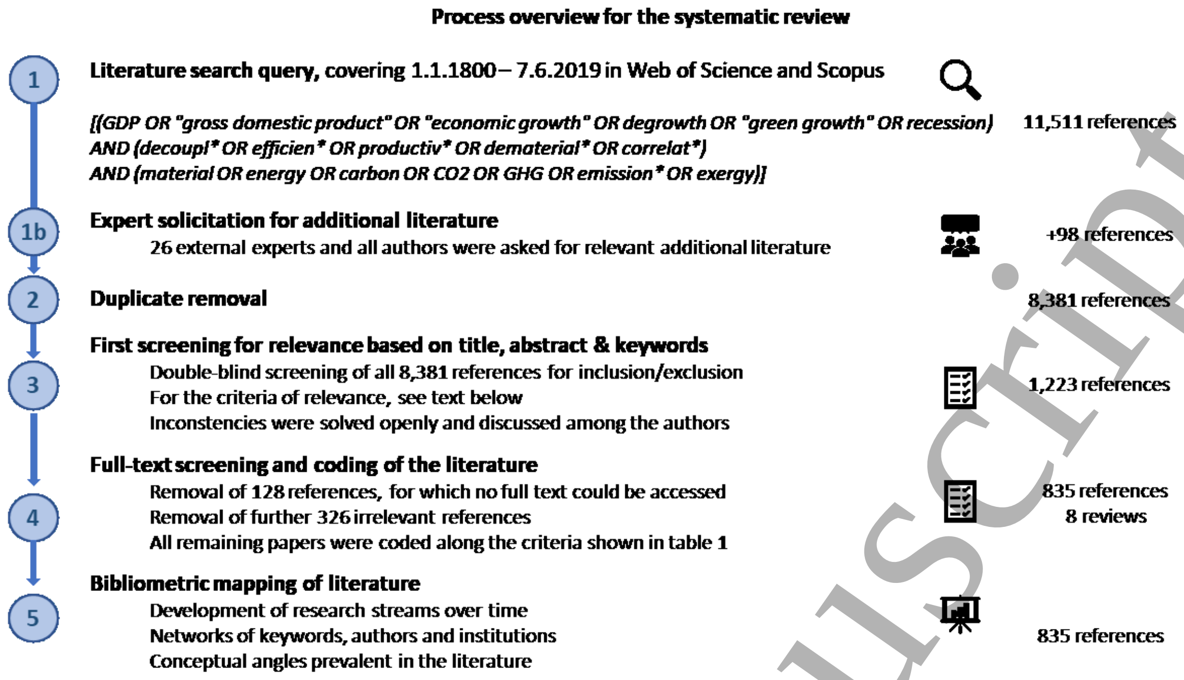

Figure 1: Overview of the systematic review process along five main steps. For the evidence synthesis please see (Haberl et al. this issue). The full list of articles including their coding can be found in the supplementary information.

Step 1 consisted of an iterative discussion process among the co-authors, supported by anonymous reviews of an early outline of this paper, to develop a *search query* (Figure 1). Through the choice of English-language keywords, this query was only for publications that – at minimum – have English-language titles, keywords, and/or abstracts. This query was applied to SCOPUS and the ISI Web of Knowledge and all 11,511 literature hits, starting with the first study found in 1972 until June 7, 2019 were downloaded. Additionally, an *expert solicitation* was conducted, to make sure that all relevant studies are covered. All authors named experts, 24 were contacted, resulting in 5 responses (see Table_SI 3). All co-authors were also allowed to add references deemed relevant; experts and co-authors together added 98 references. The systematic review platform CADIMA (Kohl *et al* 2018) was used for *duplicate removal* and the first screening phase.

In the first *screening phase,* 8,455 references were checked for relevance (Figure 1), using the criteria for inclusion/exclusion discussed in section 3. All co-authors (except B.L-G. who joined later) participated in the screening process. Title and abstract of each reference were independently assessed by two co-authors per reference to determine the relevance of the paper (allowed responses: yes/no/unclear). Differences in responses were resolved in a second round. If in doubt, a study remained in the sample (i.e. references classified as "unclear" were retained).

In the *full-text screening and coding stage* 1,169 full texts were again assessed for relevance (Figure 1, see previous paragraph) and coded according to pre-developed criteria (Table 1). Each article was coded by one co-author. 128 full texts, many of them published in unidentified or unknown journals, could not be accessed and had to be excluded. In addition, we identified 8 relevant reviews, which we used to inform our review. Another 327 references were excluded based on the full-text screening, because they did not meet the criteria for relevance (see above), leaving 835 relevant references in the final set of studies. The full list of studies, including the applied coding shown in table 1, can be found in the supplementary information.

For the *bibliometric mapping* (Figure 1), we analyzed the remaining 835 studies along the coding criteria shown in table 1 and gathered keywords, author and institutional networks. To determine the number of publications for and the connections between authors, organizations, and keywords, we used a self-developed VBA-script. The GPS coordinates of the organization locations had been gathered through the OpenCage Geocoder. To generate the network illustrations, we used the visualization software Gephi after filtering the data on the basis of a minimum publication count of four.

For the *evidence synthesis,* we refer to part II of this review (Haberl *et al* in review, this issue). In step 6, we analyze the literature to identify key empirical and theoretical findings, summarize the implications of the literature in terms of the evidence on decoupling, and aim to understand the implications for policy and strategy based on a content analysis applied to a sub-sample of 125 studies (15% of the reviewed literature).

3) Bibliometric and conceptual mapping of the literature

We here provide a quantitative overview of the decoupling literature to uncover the development of the research streams, methods, coverage and conceptual angles. We find that 92% of the reviewed studies were published between 2005 and the cut-off for this review on 06/2019. More than half of the studies (52%) were published between 2014-06/2019, while only six studies, containing 0.05% of analyses, are from <1985 (not shown in Figure 2a). Between 2005-2018, the total number of studies grew on average by +20% per annum.

3.1.) Bibliometric analysis of study scopes and indicators used

Because 252 of the 835 studies jointly analyze several indicators, for example energy and emissions in relation to GDP, and often apply several methods of analysis, we refer to the respective counts of "analyses" for each indicator/method in the following. This means that every resource/emission indicator analyzed in the literature was counted as one analysis, and that we identified a total of 1,157 analyses included in the sample of 835 studies.

We find that analyses of total primary energy supply (TPES) and CO_2 emissions from fossil fuel combustion and industrial processes dominate the literature sample and make up 42% respectively 34% of analyses (Figure 2a). Other indicators are analyzed much less, where materials and energy make up 8%, final energy 7%, full GHG emissions (i.e. including CH_4, N_2O and other gases as well as CO_2 from LULUCF) another 7% and exergy analyses only 1% of all reviewed analyses. The first studies of each thematic focus are (Smil and Kuz 1976) on primary energy decoupling for 133 countries, followed by (Kelly *et al* 1989) investigating material and energy consumption in the USA, (Nakićenović 1996) on global decarbonization (CO_2) and (Tharakan *et al* 2001) investigating GHG decoupling for 5 Asian countries.

Overall, we find that the total number of analyses being published every year increases by +20% p.a. since 2005, with different dynamics for each research stream. The total number of published analyses grows fastest for full GHG emissions (+38% p.a.), industrial CO_2 emissions (+28% p.a.) and exergy (+24% p.a.). Analyses of primary energy (+18% p.a.), materials and energy analyses (+17% p.a.) and final energy (+14% p.a.) are published relatively less.

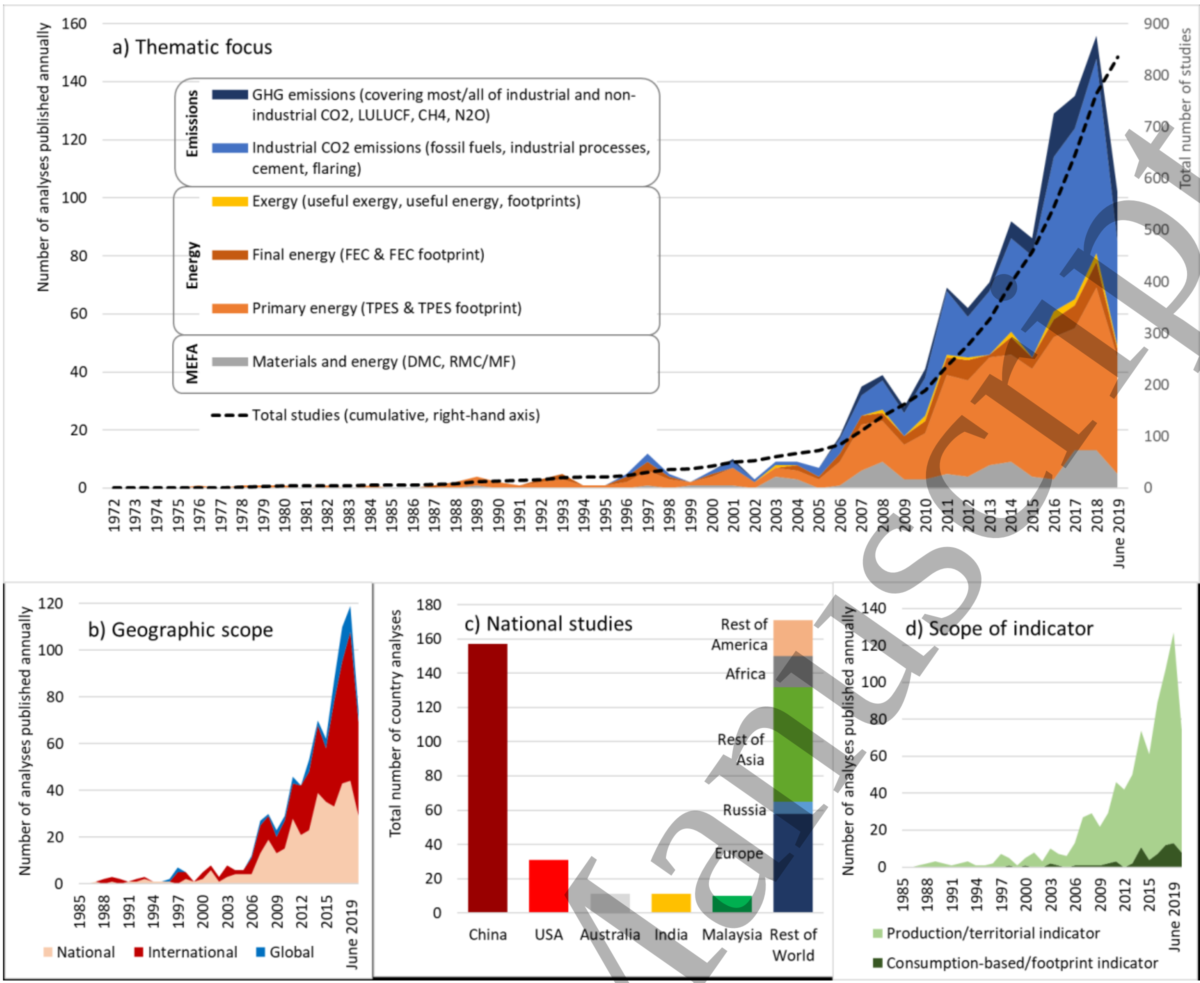

Figure 2: The development and main scope of the 835 studies published between 1976 and June 7, 2019. Please note that the 6 studies published before 1985 are not plotted in a),b),d), but are included in c). A) Thematic focus of analysis (codes 3c-3i in Table 1). B) Geographic scope of the analysis (1a-d). C) Countries analyzed more than 10 times in national-level studies, as well as continental aggregates for countries studies less than 10 times, covering all studies from 1976-2019. D) Production- vs consumption-based scope of the analysis. Because a number of studies have multiple thematic foci (e.g. energy and emissions), and/or scopes (e.g. comparing country results to global trends) there is no clear total sum, rather it depends on the categories shown in A-D See method section for abbreviations and supplementary information for the full list of the 835 coded studies.

In terms of geographic scope, we find that almost half (46%) of the analyses are single-country analyses (Figure 2b). International cross-country analyses make up another 46%, while 8% focused on aggregate global developments. Of the single-country analyses, China leads with 157 analyses, followed by 31 USA-specific analyses, then Australia and India (both 11) and Malaysia (10). Another 56 countries have been analyzed less than 10 times each, most of them in (rest of) Asia and Europe (Figure 2c). Stated differently, of the country-specific analyses, 28% investigated OECD economies, 40% China and 32% focused on other countries.

Finally, we find that the vast majority, 92% of the analyses (in 794 studies) apply a production-based/territorial system boundary (Figure 2d). Analyses applying a consumption-based perspective, i.e. taking into account all direct and indirect resource use along international supply chains, only start to appear after ~2012, when the first multi-regional input-output models became widely available (Malik *et al* 2018, Wiedmann and Lenzen 2018, Wiedmann *et al* 2011). In total, 8% of analyses (in 70 studies) utilize a consumption-based perspective, while only 4% of the analyses (in 33 studies) utilize both perspectives within the same study.

3.2.) Methods of analysis applied

In a next step, we mapped the analytical approaches taken across the 835 studies and grouping them into five broad "families" (Figure 3): cross-sectional analysis, descriptive trend analysis, decomposition and regression analysis, econometric time series analysis, and econometric causality tests. If a publication contained more than one method, for example, a descriptive trend analysis and a cross-sectional analysis, we counted that as two methods applied.

We find that of 1,542 methods applied across 835 studies, decomposition and regression analyses (28%) and econometric time-series analyses (24%) are most prevalent, followed by econometric causality tests (18%), descriptive trend (18%) and cross-sectional analyses (12%). Interestingly, there is a clear difference in preferred methods for the different research streams (Figure 3). For material and energy flows, only 9% of the methods applied are econometric time-series and 1% causality tests, while descriptive (44%) and decomposition and regression analysis (29%) dominate this research stream. For primary energy decomposition and regression analyses (25%) and econometric time-series methods (25%) are most important. Final energy and exergy have been mainly analyzed using decomposition and regression analyses (30% and 23%), as well as descriptive methods (25% and 41%). Fossil fuel and full GHG emissions have been investigated mainly via decomposition and regression methods (29% and 36%), as well as econometric time-series analyses (29% and 21%). Overall, decomposition and regression analysis are most equally distributed over all research streams, with shares between 23-34% of analyses, while econometric causality tests are most prevalent with primary energy and fossil fuel emissions (23% and 20% respectively).

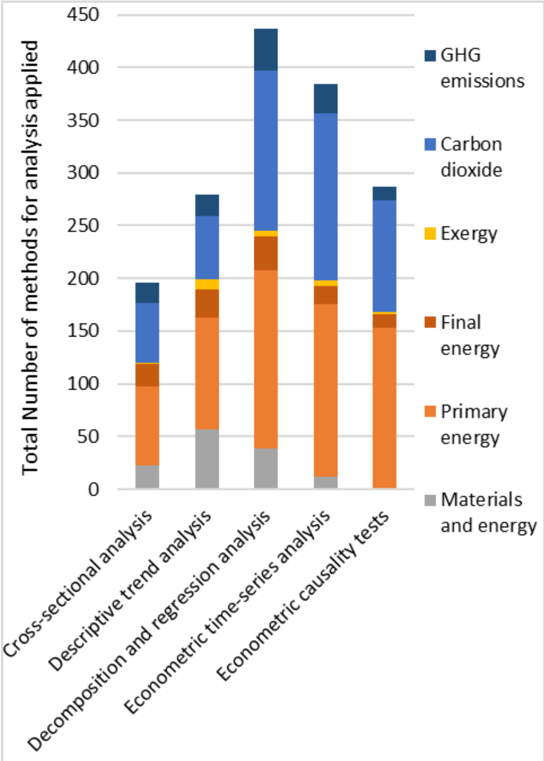

Figure 3: Number of methods applied for the different thematic foci. Methods are grouped into broad "families" of methods and thematic focus. Please note that two methods applied to the same indicator count twice (see text). Cross-sectional analysis contains for example correlations of GDP and energy across countries within the same year, while descriptive trend analysis covers comparison of GDP and resource trends or average growth rates over time. The next "family" contains decomposition and regression analyses over time, while econometric time-series analysis covers (multivariate time-dependent) statistical analysis or panel analyses. Econometric causality tests include Granger causality tests, etc. See supplementary information for the full list of 835 coded studies.

3.2.) Temporal coverage of decoupling studies by research stream

To understand the temporal perspective of the reviewed analyses and their potential insights on long-term decoupling, we mapped the temporal coverage of each empirical analysis, given proper documentation was provided. Around three-quarters of published analyses focus on the decades from 1971 onwards, with 77% of energy analyses, 85% of fossil fuels and industrial process emission analyses, 68% of material and energy analyses and 78% of GHG emission analyses utilizing data starting no earlier than 1971 (Figure 4). 50% of analyses extend over more than two decades, while 12% investigate datasets covering less than 10 years.

Studies considering decades earlier than 1971 make up 21% of all analyses and are primarily found for energy (84 analyses), CO_2 (44 analyses), material and energy analysis (17 analyses), followed by GHGs (11 analyses). The earliest empirical starting year is found in (Gales *et al* 2007) who investigated primary energy decoupling for Sweden, the Netherlands, Italy, and Spain from 1800 to 2000, and in (Apak *et al* 2011) who report on economic growth and CO_2

from fossil fuels and process emissions for the USA from 1800 to 2006. (Kovanda and Hak 2011) investigate material and energy use from 1855 to 2007 for Czechoslovakia, while (Cialani 2007) analyzed GHG decoupling in Italy from 1861 to 2002. Regarding coverage of the most recent decade, we find a reversal: 75% of GHG analyses use data including (parts of) 2009-2019, followed by CO_2 (69%), energy (58%) and materials (40%).

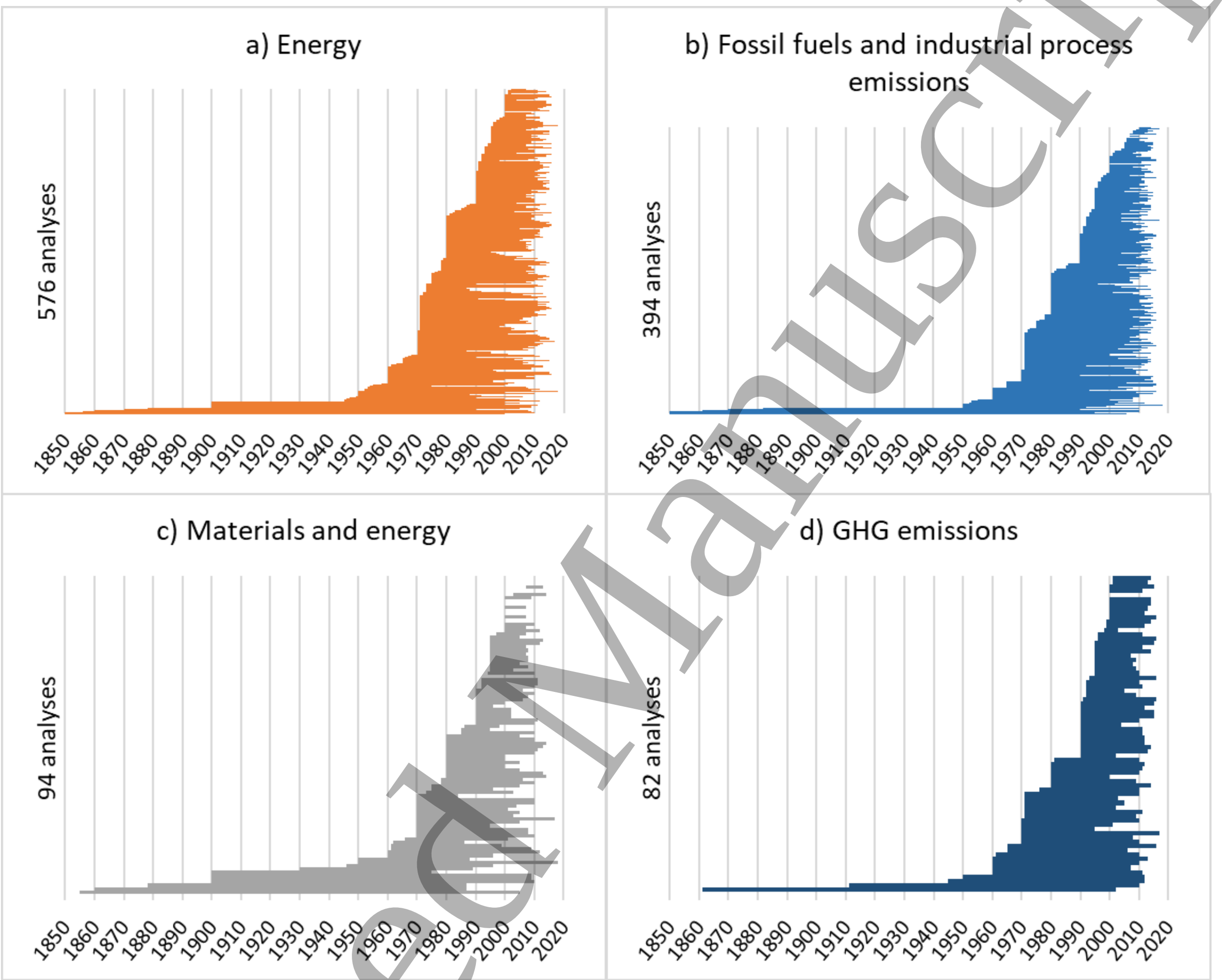

Figure 4: Temporal scope of the analyzed studies per thematic group a) Energy (3d-g), b) Fossil fuels and industrial process emissions (3h), c) Materials and energy (3c) and d) Green House Gas (GHG) emissions (3i). All primary sources where clear coverage could be identified have been included. For improved legibility, we cut-off the figures at 1850, despite a small number of studies covering earlier years. See supplementary information for the full list of 835 coded studies.

3.3.) Institutional networks in global decoupling research

We mapped the institutional networks of authors collaborating in the studies reviewed (Figure 5). Research institutions investigating decoupling are largely based in Europe, China, Japan and the USA. Members of these institutions also collaborate with one another, as determined by co-authorship, a practice especially common between the USA and China. Some work has also been done by researchers from institutions in Australia, Japan, India, Pakistan, Indonesia and Brazil, but – except for Australia and Japan – they are not strongly integrated into the decoupling research networks. Russia is hardly represented in these research networks and the same is true of the continents of Africa and South America, at least for English-language peer-reviewed literature in Scopus and Web of Science.

A mapping of institutional networks separately for the three main research streams (energy, materials and energy, emissions) indicates that while energy and emissions research follows a similar pattern as shown in (Figure 5), the joint analysis of materials and energy is mainly driven by a few institutions in Europe, Japan and Australia, with some links to China and the USA (Figure SI_1).

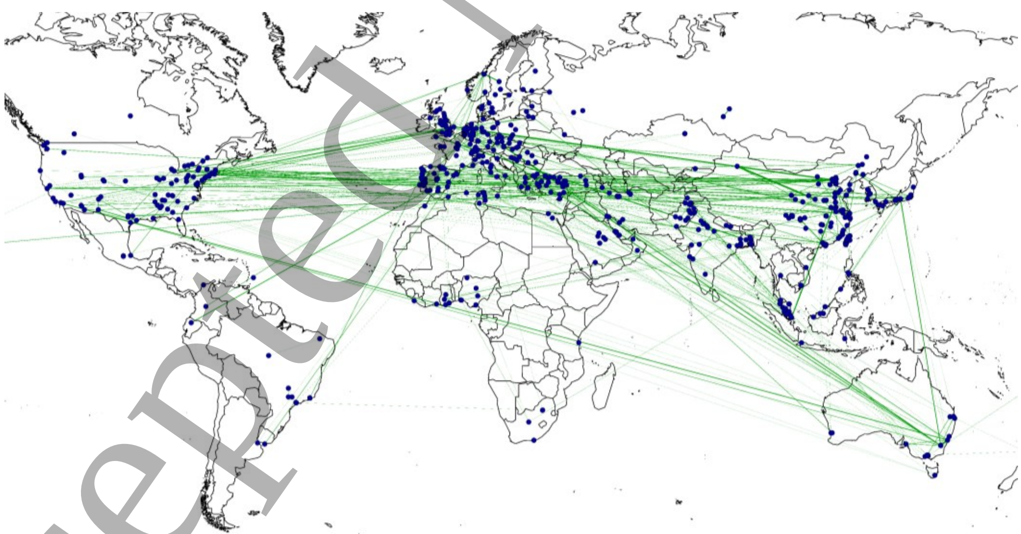

Figure 5: Global mapping of institutional networks (indicated by co-authorship) derived from the literature. A list of all the mapped institutions can be found in the supplementary information.

3.4.) Conceptual angles on the decoupling issue

As a final step, we aim to understand the major conceptual angles across the 835 reviewed studies. For this purpose, we firstly map the frequency of terms (co-)occurring in the abstract, title and keywords of the 835 papers and secondly code occurrences of the major conceptual angles on the decoupling issue (Figure 6). We start from a network of a harmonized list of semantically identical keywords used in the literature in a network weighted by frequency and (co-)occurrence and exclude all keywords mentioned less than 15 times (Figure 6a, Table SI_1). We find a major cluster of the keywords economic growth (occurring in 198 studies), carbon emissions (180) and energy consumption (153), which also tend to appear in conjunction with one another and are used as keywords in the top cited papers in our sample (Table SI_2). The five most frequently used keywords to describe the conceptual angle of the studies are Environmental Kuznets Curve (70), energy intensity and energy efficiency (62 and 59), decoupling (43), sustainable development (28) and societal metabolism (27). The five most mentioned methods are material and energy flow analysis (45), Granger causality (43), data envelopment analysis (33), cointegration (28) and input-output analysis (23). Interestingly, we note a clustering of the keywords growth, energy, financial development, GDP, cointegration, Granger causality and energy consumption, as well as another clustering of material and energy flow analysis, societal metabolism, dematerialization, industrial ecology and decoupling, indicating different theoretical and methodological approaches. These clusters and differing conceptual angles are also supported by a multi-layer network analysis of keywords, authors and author-keywords shown in (Figure SI_2).

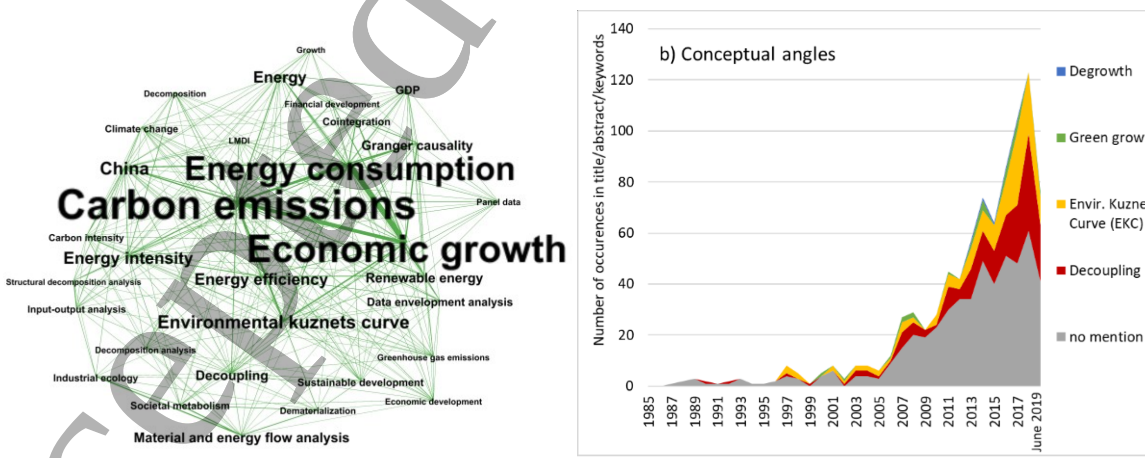

Figure 6: Mapping the major themes running through the 835 studies reviewed. A) Network of keywords (co-)occurring in the literature. The size of keyword represents the frequency of occurrence and links represent co-occurrence. Only keywords mentioned at least 15 times are shown. Green nodes & lines: keywords (mentioned at least 15 times) and keyword network. B) Frequency of explicit mention of key conceptual angles in title/abstract/keyword. Note that six analyses before 1985 are not shown. See supplementary information for the full list of 835 coded studies.

To get a final insight to what extent the reviewed literature situates itself explicitly within specific conceptual angles on economic growth, we coded all 835 studies for the occurrences of the terms Environmental Kuznets Curve, green growth, degrowth and decoupling in their respective title/abstract/keywords over the entire time period (Figure 6b). We find that most studies (524 of 835 studies) do not mention any of these terms, while decoupling is mentioned most often (174 occurrences), followed by the Environmental Kuznets Curve (138 times). Green growth (24) and degrowth (5) are hardly used in title/abstract/keywords. Interestingly we find that since around 2011 more and more studies explicitly relate to these concepts and in 2018/19 45% of studies explicitly mention decoupling or the EKC. For further in-depth qualitative interpretations of these conceptual issues we also refer to part II of this review (Haberl *et al* in review, this issue).

4) Discussion: how do the research streams approach decoupling?

In this section, we discuss how the literature in the three research streams approaches the decoupling issue, reflect on the major conceptual contributions to the topic and draw some conclusions on potential next steps.

4.1.) Research on energy decoupling

The energy research stream uses several indicators for energy use, which differ regarding the point of reference within the energy conversion chain and thereby provide differentiated insights into the interdependencies with economic growth. This complexity is often under-appreciated in the majority of the energy decoupling literature and also in most of the energy-growth econometric 'causality' reviews (Ozturk 2010, Tiba and Omri 2017). The most commonly used indicator is total primary energy supply (TPES), referring to the energy content of all energy carriers prior to subsequent conversion steps (e.g. coal, oil, biomass). Further indicators are final energy consumption (i.e., the energy provided to end users after conversion processes, e.g. electricity or district heat) and useful energy consumption (i.e., the energy after conversion in end-use devices, such as low-temperature heat provided by residential heating systems, or kinetic energy provided by car engines).

Clearly, efficiency and decoupling potentials differ strongly depending on these different aspects of energy for socio-economic activities. It is also argued that exergy, which measures the share of energy capable of performing mechanical, chemical, or thermal work provides a more precise measure to study the significance of energy for society and economic development (Ayres and Warr 2005). Despite the fact that 'exergy studies' have clearly enriched the debate about the relationship between energy and GDP, studies applying an exergy perspective are still the exception (Figure 2). The longstanding history and differentiations of energy decoupling research are also reflected in the relatively loose network of collaborators publishing on the subject (Figure SI_3).

About one-third of the energy analyses focuses on the causal interrelations between energy and GDP (Figure 3). Most of these studies are more or less exclusively interested whether energy use drives GDP, or conversely GDP drives energy use, often relying on Granger causality tests or similar methods. While often quite elaborate in terms of statistical methods, most of these studies show scant if any interest in the precise meaning of the energy indicators analyzed. Many do not even explicitly state whether the energy indicator used refers to primary or final energy; indeed, for a large number of studies we had to go back to the cited data sources to find that almost all these studies had analyzed primary energy. Also, most of the existing reviews ether do not even examine their literature for these issues, while (Kalimeris *et al* 2014) note that the inconclusive and inconsistent outcomes might be due to what they call "measurement problem". We find, that additionally to the conceptual and methodological issues around econometric causality tests (Stern 2011, Kalimeris *et al* 2014), more useful conclusions could be drawn from a sound theoretical understanding of energy conversion chains, their relation to economic activity and the role of efficiency gains and rebound effects (Stern 2011, Parrique *et al* 2019, Hickel and Kallis 2019).

In contrast, the "exergy" literature (including that concerned with final or useful energy) is conscious of the thermodynamic underpinnings of these energy indicators; a substantial fraction of this literature is not using econometric methods to analyze interdependencies but incorporates energy indicators in macro-economic production functions, i.e. uses a theory-based approach. For this literature, the relationship between economic growth and energy use is based on the hypothesis that energy is an important production factor in the economy (Ayres and Warr 2005, Kümmel 2011, Brockway *et al* 2017, Stern 2011). Thus, according to this strand of research, economic growth cannot be fully explained without considering the amount of exergy available and the efficiency with which it is converted in useful work.

Overall, the research concerned with energy provides a rich picture on the interdependence between energy at its various conversion steps and economic growth, often using econometric time-series or causality testing methods. However, analyses covering several of these indicators are rare (40 studies), as are analyses systematically integrating production- and consumption-based perspectives (10 studies).

4.2.) Research on resource use (materials and energy) decoupling

Material and energy flow analysis (MEFA) is occupied with generating a comprehensive account of the physical exchanges of materials and energy between socio-economic and ecological systems (Fischer-Kowalski *et al* 2011, Krausmann *et al* 2017, Zhang *et al* 2018). MEFA provides aggregate and harmonized indicators, measured in metric tons respectively joules, in line with the system of economic-environmental accounts. MEFA studies add dimensions that are not considered in energy studies: biomass used as food and feed (Haberl 2001), timber and other biomass-based products, non-metallic minerals and metals used to expand and maintain material stocks of infrastructure, buildings and machinery, as well as short-lived products (e.g. road salt or fertilizer) (Krausmann *et al* 2017). In this manner, comprehensive accounts of the so-called societal metabolism of metals, non-metallic minerals, fossil fuels and biomass have been developed.

Conceptually, this research stream starts out from a complex socio-ecological systems perspective on the socio-metabolic interdependencies between materials, energy, waste and emissions (Haberl *et al* 2019, Pauliuk and Hertwich 2015). This includes the necessity for a differentiated perspective on resource efficiency along material and energy conversion chains (Zhang *et al* 2018), and the importance of international trade, i.e. the relevance of production-based and consumption-based approaches (Haberl *et al* 2019, Zhang *et al* 2018, Krausmann *et al* 2017). Datasets are increasingly becoming available that go beyond aggregate indicators and trace materials and energy carriers from extraction to final uses, their accumulation in stocks of manufactured capital and the resulting wastes and emissions, strictly following thermodynamic principles and mass-balances (Krausmann *et al* 2018, Schandl and Miatto 2018, Kovanda 2017, Vilaysouk *et al* 2019, Martinico-Perez *et al* 2018). These efforts, especially when taking into account the available complexity of energy indicators along the entire conversion chains, could provide innovative systems-based insights into resource decoupling.

Empirically, most studies so far are limited to aggregate indicators of resource extraction, trade and domestic material and energy consumption measured in metric tons, increasingly also for the material footprint. Data availability and the need for harmonizing methods over the last 20-30 years favoured studies on the EU's member states, Japan and China, which is also reflected in the institutional collaboration networks (Figure SI_1). Material and energy flow studies are performed by a relatively close network of collaborators, which were also involved in method development (Figure SI_3). The analysis of resource decoupling between aggregate material and energy flows and GDP are often only an "add-on" in this research stream and are usually limited to descriptive trend analysis or cross-sectional efforts. Only recently, partially due to international datasets from Eurostat and UNEP becoming available, decomposition and regression analyses methods increasingly enter the scene (30%), as do econometric time-series (9%) and econometric causality tests (1% of all MEFA analyses reviewed) (Figure 3).

4.3.) Research on emissions decoupling

Investigations of territorial CO_2 emissions from fossil fuel combustion and industrial processes such as cement manufacture require less own empirical quantification efforts than MEFA-studies because these emissions can be directly calculated stoichiometrically from fuel use respectively cement production data. Many of the issues from the energy research stream therefore also apply here. Long term national time series data on these emissions have been readily available for quite some time from sources such as the Carbon Dioxide Information Centre (Marland *et al* 2016), the International Energy Agency or the World Bank Development Indicators, although with slightly varying information and inclusion/exclusion of industrial processes. Hence, there is a large literature on the (mostly relative) impact decoupling of GDP from territorial CO_2 emissions, also see reviews by (Mardani *et al* 2019, Parrique *et al* 2019).

By contrast, full territorial/production-based GHG accounts also need to quantify emissions from land-use and land-cover changes (LULUCF) as well as highly uncertain and strongly context-dependent emissions such as those of CH_4 and N_2O. Comprehensive assessments of GHG emissions over many decades (in particular with relation to the LULUCF component for long-term changes in carbon stocks in soils and above-ground biomass) are only recently becoming available and will add important new aspects to the decoupling issue (Gingrich *et al* 2019). The literature analyzing GHG-GDP impact decoupling is therefore quite driven by the improvement in data availability over time.

The quantification of carbon or GHG "footprints" started a bit over a decade ago and has advanced rapidly (Hertwich and Peters 2009, Lenzen *et al* 2013, Peters *et al* 2011, Peters and Hertwich 2008, Peters *et al* 2012, Wiedmann and Lenzen 2018). Most studies include fossil-fuel and industrial-process related GHG emissions, whereas LULUCF related GHG emissions are not systematically accounted for due to data constraints and challenges in attributing LULUCF emissions to specific sectors and over time.

We find that CO_2 emissions from fossil fuels have been analyzed 389 times (34% of all analyses in 835 papers), 7% of which apply a consumption-based indicator. For GHG emissions we find 74 analyses (6% of all analyses in 835 papers), and a rather large share of 16% or 12 papers applying a consumption-based approach. While decomposition and regression analysis are similarly prevalent for this research stream as in the others, we find that interestingly, for CO_2 emissions econometric time-series (30%) and causality tests (20%) are used quite often.

4.4.) The empirical basis and development of the three research streams

We note large imbalances in the number of analyses done on energy, materials and energy, as well as emissions (Figure 2). To some extent these imbalances are related to differences in the availability of standardized data in easily accessible databases, such as from the IEA or the World Bank, also reflecting how mature and widely accepted certain indicators are. For example, large-scale gathering of standardized and comparable global data for primary energy research originates in the 1970s; CO_2 emissions from fossil fuels, which are high on the economic, political, and scientific agendas, can directly be derived from data on energy consumption. However, publicly accessible useful energy/exergy data has only recently become available for analysis (Sousa *et al* 2017). Material and energy flow analysis has been adopted into standardized statistical reporting only in the last ~15 years (Fischer-Kowalski *et al* 2011, Schandl *et al* 2017) and recently UNEP started hosting a global database (UNEP-IRP 2019).

The development of harmonized international datasets on full GHG emissions that include CO_2, CH_4, N_2O, other GHGs as well as land use became an issue only in the last 10-20 years. Given constraints on the temporal coverage for all indicators, only a small number of analyses cover the full process of industrialization over the last 100+ years (Figure 4). However, such long-term perspectives on economic growth, resource use and emissions are highly relevant as the majority of countries are still in the midst of the transition into fossil fueled industrialization.

These data issues may also explain why in younger fields with less standardized databases often more effort is directed at the generation of a robust dataset and descriptive analyses of patterns and trends prevail (Figure 3). We also find that the statistical complexity of the method of analysis does not automatically translate into more robust insights, since in many studies a transparent documentation and an in-depth understanding of the applied resource use or emissions indicators is often lacking, substantially limiting the conclusions that can be drawn.

We also find a dominance of studies on industrial/OECD economies and China in terms of geographical coverage, while the global South is not covered well. On the one hand this is related to issues of data availability, on the other hand it reflects the significance of achieving decoupling, which is more urgent for industrialized and emerging economies. As our mapping of research institutions involved in English language peer-reviewed literature indicates, build-up of know-how seems to mainly occur in the industrialized countries of the northern hemisphere and China. Investigating publications in other languages might shed additional light on this question but was out of scope of this review. Still, better knowledge for the Global South is urgently required, as these countries are in the midst of industrialization processes and could still avoid resource and emission intensive lock-ins.

5) Conclusions: status quo for decoupling studies and the way forward

The idea of economic growth was termed the most important conceptual innovation of the 20th century (McNeill 2000) and it has become synonymous with limitless societal progress and improved well-being for many politicians and large parts of the general public (Schmelzer 2015, 2016). While criticism of GDP as the central policy indicator and its growth as a political achievement is mounting (Costanza *et al* 2014, Hoekstra 2019, Hickel and Kallis 2019, Parrique *et al* 2019, Jackson and Victor 2019), the growth imperatives for firms and corporations and, by extension, for their political champions, give it staying power in the actions of business managers and policymakers. Hence, it remains a highly relevant question whether the continued focus on economic growth fuels the rapidly accelerating sustainability and climate crisis and to what extent research addresses these issues.

From our systematic review, we find that the literature dealing with decoupling of economic growth, resource use and emissions has been growing rapidly since ~2005, with a compound annual growth rate of 20% p.a. in the total number of published studies. We systematically identified a total of 835 studies presenting empirical analyses of 1,156 indicators on the relation of economic growth with material and/or energy and emissions. The majority of indicators analyzed for potential decoupling are primary energy (42%) and industrial fossil fuel emissions (34%). Analyses of final energy and exergy (7% and 1%), material and energy flows (8%), as well as full GHG emissions (7%) are still relatively rare. However, these topics are also highly dynamic, where we find high compound growth for analyses of GHG emissions, industrial carbon emissions and exergy (38%, 28% and 24% p.a. respectively), while analyses of indicators on final energy, materials and energy, as well as primary energy show relatively lower but still high growth (14%, 17% and 18% p.a.).

We identify three points specifically important for future research on this topic. Firstly, consumption-based perspectives are crucial innovations in the decoupling discussion, because they enable capturing the effects of growing international trade and potential burden shifting along supply chains. Since the early 2010's the required global multi-regional input-output modelling capabilities have become widely available and studies are starting to take up on these datasets, although still making up only 8% of all analysis reviewed herein. Lately also income-based responsibility has been put forward as another perspective, which focuses on the enabling of downstream resource use and emissions by upstream extractive economies and industries

(Marques *et al* 2012, 2013, Steininger *et al* 2015). However, that perspective has so far rarely been taken up in the reviewed literature. For income- and consumption-based approaches, which both rely on input-output modelling, two key challenges await (Wiedmann and Lenzen 2018, Malik *et al* 2018, Tukker *et al* 2018): a) methodological refinements in multi-layer representations of physical and monetary aspects of supply chains as well as nesting cities, countries and the world economy, and b) accelerated data gathering and model updates, which is constrained by the need for statistical offices to report the underlying information. The combination of production- with (income-) and consumption-based accounting is highly valuable for informing environmental policies, evaluating responsibility for resource use and emissions (Jakob and Marschinski 2013, Schaffartzik *et al* 2015, Steininger *et al* 2015) and assessing the prospects for relative and absolute decoupling. However, only 4% of the 835 reviewed studies used a combined analyses of production- vs consumption-based indicators.

Secondly, we propose that substantial advances in theoretical and empirical understanding of resource and impact decoupling can be achieved by utilizing a systems-based and thermodynamically grounded perspective as put forward through the socio-economic metabolism, to conceptualize the interdependencies between energy and materials conversion chains (resources), and the resulting wastes and emissions (impacts). Socio-economic activities (such as increasing production and consumption as well as complexity of distribution) directly or indirectly inevitably require materials and energy in various forms. They are utilized to provide functions and services to society by utilizing stocks of infrastructure, buildings and machinery, ultimately and necessarily resulting in waste and emissions (Haberl *et al* 2017, Pauliuk and Müller 2014, Weisz *et al* 2015). These interdependences between the socio-economic system and its biophysical basis are fundamental to understanding the role of economic growth and prospects for absolute resource and impact decoupling at the required scale and speed (Haberl *et al* 2019, Pauliuk and Hertwich 2015).

Thirdly and finally, a major conclusion of this systematic review is that the vast majority of studies originates in decompositions, causality tests, or related Environmental Kuznets Curve analysis, which approach the topic from a simplistic statistical econometric point of view. We find that they hardly incorporate a thermodynamic understanding of resource use and especially energy, and economic growth and rarely take the large-scale consequences of growth dynamics for the climate system into account. In contrast, the socially relevant discourses on modifying the growth narrative into "green growth", or more substantially, "degrowth & post-growth", are only sparsely treated in the quantitative literature reviewed herein. This points to a huge gap between social scientists interested in the meaning and social significance of the growth discourse, and the analytical epistemic community concerned with the statistical relationship in its various facets between economic growth and environmental pressures and impacts. A theoretically grounded and critical approach to the roles of and causalities between economic growth in society and for the environment could greatly benefit from such an interdisciplinary endeavor and bring new and potentially socially highly relevant insights to the decoupling issue.

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Data availability statement

The data that support the findings of this study are openly available. We refer the interested reader to the supplementary data file and supplementary information.

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