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The Material Intensity of Growth: Implications from the Human Scale of Production

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Abstract Contemporary empirical studies on the resource intensity of the economic process provide evidence of a gradual de-linking between natural resources use and economic growth. Resource intensity is evaluated through the Domestic Material Consumption/Gross Domestic Product (DMC/GDP) ratio, defined as the material intensity index. Trajectories of this ratio support the optimistic view that economic output is becoming progressively less dependent on resource flows, hence GDP is gradually dematerialized. The present study asserts that the DMC/GDP indicator fails to take into account the biophysical properties of the production process which define the resource requirements of the economy. The present study proposes the "resources required for producing one unit of GDP per Capita (Income)", as an alternative indicator for evaluating the resource requirements of the economy. The resource requirement, evaluated at the level of income, approximates the human scale of production; goods should embody certain biophysical properties in order to satisfy human needs. The trajectories of DMC/Income index for global growth rejects the vision of a dematerialized growth and the de-linkage of the economy from natural resources.

Keywords Decoupling · Dematerialization · Natural resources scarcity · Economic development · Sustainable development · DMC/Income

JEL Classification O44 · O50 · Q32 · Q57

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Abbreviations

DMC Domestic material consumption
MFA Material flows analysis (or accounting)
HSP Human scale production
MI Material intensity

1 Introduction

Contemporary literature salient to the linkage between economic growth and resource use asserts empirical evidence for a transition to an era of relatively dematerialized production (Goodall 2011; Herman et al. 1990; Hawken et al. 1999; Wölfl 2005). Material intensity (MI) defined as the amount of resources required for producing one unit of GDP, has demonstrated a decreasing trend since the 1950s for the global economy, marking a strong decoupling period (Dittrich et al. 2012). Technological progress allowed the efficient use of material resources; the production process was reengineered; goods and services were redesigned; and substitutions with lighter materials resulted in the production of lighter goods. Expectations of technological advances, coupled with a shift in developed countries towards the service sector, raise optimism as to a further dematerialization of the economic process and, hence, sustainability prospects.

Recent empirical estimates could be seen as the empirical aftermath of the old, but still essential, inquiry into the necessity of natural resources in economic production and the "limits to growth" imposed by natural resource scarcity (Tepperman 1981; Mackellar and Vining 1989). To recall two prominent approaches, Solow's early work with the aggregate Cobb–Douglas production functions (Solow, 1956, 1957) supports the assertion that materials are unimportant, since material flows could be substituted almost perfectly by manmade capital. "*The world can, in effect, get along without natural resources*" (Solow 1974, p.11). This approach is further corroborated by later studies (Baumol 1986; Solow 1978). On the other hand, Georgescu-Roegen (1971, 1975, 1976), based on "flow-fund" production functions, verifies constraints on growth implied by the entropic scarcity of natural resources (Daly 1997).

Recent empirical studies assess the MI of economies by means of the methodological principles of the economy-wide material flow analysis[1] (MFA). The principal indicator for the evaluation of material intensity is the Domestic Material Consumption/Gross Domestic Product (DMC/GDP)[2] ratio, estimating the material inputs required for the production of one unit of GDP. (Krausmann et al. 2009, 2011; UNEP 2011). The relevant findings indicate that material intensity declines almost constantly at the global level and raise optimism over the potentials for a dematerialized economy with sustainability prospects (Schandl and Turner 2009; Schandl et al. 2015).

The present study questions these findings and attempts to re-evaluate the material intensity of global economic growth over the last 100 years. Our estimates, substantially

[1] Or *Material Flow Accounting*. MFA quantifies and monitors the physical properties and dimensions of economies and provides information about the amounts of natural resources entering the socio-economic system. The use of natural resources is measured and reported with standardized accounting methods which permit the development of long run time-series data.

[2] Where DMC = Domestic Extraction (DE) + Material Imports (MI) − Material Exports (ME).

different from the prevailing ones, result in serious implications for the prospects of sustainable development and for the contemporary debate over a-growth and de-growth. (Howarth 2007; Kallis 2011; van den Bergh 2011; van den Bergh and Kallis 2012).

We propose the ratio *resource inputs required to produce one unit of "GDP per Capita",* DMC/[GDP per Capita], as an improved approximation of the link between resource consumption and the economy. "GDP per Capita" stands as the broadly used monetary-based index of the utility enjoyed by one individual. The utility of one individual is usually denoted as "income", the key economic variable for evaluating the performance of the socio-economic system. The analysis remains within the monetary realm which permits the use of long-run datasets and direct comparison with the standard DMC/GDP index.

"GDP per Capita", as a basis for the evaluation of the MI, brings into the analysis the reason, the "cause", of the economic process. The economic process aims at the satisfaction of human beings and therefore the outcome of the economic process ought to be envisaged on the human scale. Once the economic process is envisaged on the human scale, the physical properties of goods can be better approximated. Goods should irrevocably possess certain physical properties in order to satisfy human needs, and these properties set certain limits on the resource requirements. In this context, DMC/[GDP per Capita] evaluates the MI at the boarders of the economic system by comparing resource inputs with actual outcome, the utility arising from the consumption of goods. As the utility is an individualistic perception, "GDP per Capita" emerges as the appropriate monetary indicator for defining the outcomes of the economy. Aggregate GDP reveals the scale of the economy; however, the actual outcome cannot be approximated without taking into account the number of human beings processing GDP.

DMC/[GDP per Capita] defines the resources required for the creation of one unit of utility defined as the income available to the "average" citizen for the consumption of goods and services; DMC/[GDP per Capita] could be defined as DMC/Income (where, GDP per Capita = Income). The difference with the standard DMC/GDP index is essential and extends beyond their algebraic structures, as it concerns the very essence of the economic variables considered.

The evaluation of the MI at the income level sets the decoupling debate within the complexity of the Coupled Human and Natural Systems (CHANS). (Liu et al. 2007; Mavrommati et al. 2014, 2016) The economy, as a Human Scale Production (HSP) process, takes place within the dynamic interaction of Coupled Human and Naturals Systems (CHANS). The income level, contrary to the aggregate GDP, constitutes a monetary variable defined on the human scale with clear reference to the human system. Such an approach creates a better understanding of the dynamic relations between social and economic activities and the environment. As a result, the proposed indicator may contribute to the sustainability analysis by offering an operational index which better approximates the dependency of economic growth on natural resources.

The present study focuses on a subcategory of resources, namely, the *mass* resources. Contemporary studies mainly examine the linkage between growth and total resource usage, defined as the material flows of fossil fuels (oil, coal, natural gas); biomass; ores-industrial minerals; and construction minerals. In addition, a number of studies focus on the link between growth and energy resources. A disaggregate consideration of mass resources has not sparked the interest of the analysis, although they do play a distinct role in the production process. Mass inputs create the scaffold—the "body"—of goods, while energy inputs provide the power for processing mass inputs. The present study limits its scope to the link between pure mass resources and economic growth. We compare world[3] DMC_{mass}/GDP and world DMC_{mass}/Income estimates. To define mass resources, we subtract energy (fuel) resources from aggregate resource use (See data section, for more details). It goes without saying that we do not suggest DMC_{mass} as an alternative to total DMC; we simply focus on a subcategory of total DMC, specifically that of mass resources. Our estimates are based on the Material Flow Analysis (MFA) framework which permits the use of reliable, recently developed datasets and comparability with other relevant studies. To the best of our knowledge, this is the first time that the mass (non-fuel materials) intensity is estimated at the global aggregate level.

The present paper is organized as follows: Sect. 2 reviews the relevant literature on the decoupling effect and the material intensity dialogue; Sect. 3 presents the proposed framework for the (re-)estimation of decoupling; Sect. 4 briefly presents the databases employed for the purposes of our estimates; Sect. 5 presents the analysis and the results of the estimated decoupling effect at both the global aggregate and disaggregated level, as well as the estimation of the so-called Decoupling Index (DI); and, finally, Sects. 6 and 7 contain further discussion of the results and the overall concluding remarks, respectively.

2 Decoupling and Material Intensity: A Brief Literature Review

The early attempts to estimate material intensity (Malenbaum 1978; Tilton 1977), as well as the latest empirical analysis (Krausmann et al. 2009; UNEP 2011; Schandl and West 2012) assert that global aggregate material use has increased at a slower pace than the global economy—GDP growth—during the last century (Fischer-Kowalski 2011). This denotes the so-called decoupling of economic growth from material resource inputs, the "dematerialization" of the economic process (Wernick et al. 1996). Relative decoupling seems to be fairly common in the relevant literature (UNEP 2011), while there are also a few studies providing empirical evidence for absolute[4] material decoupling (De Bruyn 2002; Goodall 2011; Krausmann et al. 2011).

The decoupling literature mainly distinguishes three factors which explain the declining trends in material intensity: technological progress; substitutions among materials; and structural changes in GDP towards services (De Bruyn 2002). Concerning technological progress and material substitution, Bernardini and Galli (1993) attempted to establish a theoretical framework suggesting that research in material technology and substitutions among different material types could bring about substantial gains in the dematerialization of the economic process. The structural change hypothesis asserts that during the early phases of industrialization, economic growth (GDP) results in an increasing use of material resources; when the country enters the post-industrial phase, material resource use starts to decline (Kander 2005), as a result of reorganization of the economy toward services (Panayotou 1997; Hawken et al. 1999; Panayotou et al. 2000; Stern 2004). The combined forces of technological progress, material substitution, and structural changes in the

[3] While DMC is a notion mainly used for national economies, we use the "world DMC_{mass}" to define the global aggregate non-fuel materials consumption, in accordance with the relevant literature which uses the "DMC" notion at the global level, as well (i.e. Krausmann et al. 2009).

[4] The literature distinguishes the decoupling effect into two distinct categories: relative decoupling and absolute decoupling. Relative decoupling means that the growth rate of the resource used is lower than the rate of economic growth (GDP), while absolute decoupling is defined as the decline in resource use irrespective of the economic growth rate (UNEP 2011, p. 5).

economy, induce a transition to a post-industrial dematerialization era of economic production (Behrens et al. 2007; Brooks and Andrews 1974; Hawken et al. 1999). Many studies acknowledge dematerialization as an important factor in moving towards the achievement of long-term sustainability (Ausubel and Waggoner 2008; Hekkert 2000; Giljum et al. 2005; von Weizsaecker et al. 1998; Hatfield-Dodds et al. 2015).

On the other hand, a large part of the relevant literature questions the potential for further dematerialization. Taking into account the rapidly developing countries, many suggest that growth in China and India has triggered material intensity further, despite the achievements of technological progress. Such a trend may finally push the global system to the unsustainable boundaries of resource availability (Schandl and Eisenmenger 2006). Further "*pessimism*" over the future potential of decoupling arises from the consumption trends of the western lifestyle, a lifestyle being adopted by more and more developing countries which entails substantial material requirements (Reisch and Røpke 2004; Røpke 2001; Wernick 1996). Furthermore, some studies (Trainer 1999; Vogely 1976; Wernick et al. 1996) support the idea that, if a trend away from manufacturing is truly occurring, it would not necessarily lead to less material use, since the service sector generates its own material requirements. In that context, many (Auty 1985; Cleveland and Ruth 1999; Herman et al. 1990; Røpke 2001) question a service economy's potential for bringing about dematerialization, while others claim that the slowdown in material intensity may be a fallacy in terms of real production (Herring 2006; Jackson 2009; Kander 2005; Lawn 2001; Trainer 2001). More radically, Ayres and Warr (2004) conclude that evidence points to the fact that dematerialization cannot be achieved except by putting an end to economic growth, a view that is further supported by some recent studies (Heinberg 2011; Jackson 2009; Martenson 2011; Daly 2013).

3 The Human Scale of Production and Implications for Material Intensity

The efficiency of a system should be estimated at its borders by comparing actual inputs with actual outputs. The ratio by which inputs are transformed into outputs indicates the way in which the system performs to produce actual outcomes. According to this rationale, the link between the economy and resources should be evaluated by estimating the material requirements of the final, the ultimate, outcome of the economy. An economy produces exchangeable goods whose consumption satisfies human needs. The economic welfare/utility, arising from the satisfaction of human needs stands as the ultimate objective of the economy. Within the monetary framework, welfare/utility is measured through one of the most commonly utilized economic indexes, that of "GDP per Capita". Contemporary research has proposed various alternative monetary measurements of economic welfare, such as the Index of Sustainable Economic Welfare (Daly and Cobb 1989), the Human Development Index (Stapleton and Garrod 2007), the Index of Economic Well-Being (Thiry 2015), and the Genuine Progress Indicator (Costanza et al. 2014). In addition, many countries have developed "Quality of Life" (QOL) qualitative indexes and statistics that attempt to measure quality of life, as an alternative to monetary indicators (Hagerty et al. 2001). All these contemporary approaches still have many differences in their theoretical foundations. Furthermore, the availability of data sets is extremely limited and the potential for empirical analysis seriously constrained (ibid). Under these restrictions, the use of GDP per Capita still remains the predominant measurement of economic welfare in the vast majority of international reports and statistics (EU and OECD 2012), despite its well-recognized shortcomings (Dowrick 2007; Costanza et al. 2014). The existence of long-run datasets with relatively reliable data on "GDP per Capita" has further promoted its use as the appropriate indicator for the macro approximation of the very essence of economies. (Maddison 2003, 2008; EU and OECD 2012; OECD 2013) The classification of countries into developed and developing ones is an eloquent example of the use of GDP per Capita as predominant macroeconomic indicator for approximating the actual outcome of the economies.

An economy is evaluated, ceteris paribus, on the basis of the income enjoyed by the average individual. Within this context, the estimation of the MI for the creation of one unit of income is a satisfactory approximation for the actual resource efficiency of the economic process, which is an engine that transforms material inputs, combined with other production factors, into the utility enjoyed by human beings, reflected in monetary terms, by the income available to individuals. On the other hand, GDP reflects the scale of the economy; an aggregation defined regardless of the number of individuals served. The actual outcome of the economy can only be estimated as the utility provided to the citizens. Therefore, the number of citizens should be taken directly into account, as economies of the same GDP level may provide substantially different levels of welfare, once different population levels are served by these economies. Let us assume two economies of the same scale reflected by the very same aggregate GDP (Table 1).

The two economies differ in their population sizes as economy B aims at satisfying the needs of a population twice as large as that of economy A. As a result, the GDP per Capita of Economy A is double that of Economy B, indicating, ceteris paribus, that its citizens enjoy twice as much economic welfare/utility, also twice the purchasing power, and thus twice the income. The MI, defined as DMC/GDP, is exactly the same for both economies, indicating that one unit of GDP requires the very same resource inputs. However, this MI estimate cannot take into account the essential output of the two economic systems which are fundamentally different as they provide different levels of welfare to their citizens. The DMC/Income index evaluates the material requirements of the actual outcome of the two economic systems, the utility, as it is approximated by the income available to the citizens. And the material requirements of the ultimate outcome of economy B emerge as twice those of economy A. Indeed, economy A is much more effective in the use of resources since the same aggregate amount of resources provides two times the level of income for its citizens than economy B.

The present study argues that the prevailing decoupling estimates, made at the level of the aggregate GDP, conceal important aspects of the link between the economy and resources. The main reason is that aggregate GDP is not sensitive, even indirectly, to the physical aspects of production (Bithas and Kalimeris 2013, 2016). The MI is irrevocably the composite effect of the physical properties of the goods produced. As GDP stands at the highest level of monetary abstraction, it is not sensitive to the physical properties of goods which determine the actual material requirements of the economy. Indeed, GDP reflects the aggregate of the monetary value of all goods produced through the economic process and hence, GDP stands as a monetary amalgam that homogenizes all production in monetary terms. The overwhelming effects of the current growth trends of the "dematerialized" sectors of the economy—such as financial services, social media and other knowledge-based activities—render a picture of a drastically dematerialized GDP. However, before consuming the less materially-intensive goods, human beings need to satisfy their basic needs (such as, thirst, hunger, shelter, transportation, etc.) which require goods with substantial material requirements. The allocation of aggregate production between basic and "dematerialized" (services) goods depends on the population level, a variable that determines the GDP per Capita (income) index, while aggregate GDP remains insensitive to population level.

Table 1 Comparing two indicative hypothetical economies

Economies	DMC (tons)	Population (pers.)	GDP ($)	Income (welfare in $)	DMC/GDP (kg/$)	DMC/Income (kg/welfare$)
Economy A	1000	2500	$10,000	$4	0.10	250
Economy B	1000	5000	$10,000	$2	0.10	500

The MI reflects the physical aspects of the economy, the goods produced, and therefore, it should be evaluated at a monetary level at which its physical properties are traceable. By downscaling aggregate GDP to the level of "income", we evaluate the material requirement for the average basket of goods consumed by the citizens. "GDP per Capita" refers, ceteris paribus, to a set of goods whose physical properties can be traced, even indirectly. The set of goods, reflected by the GDP per Capita index, approximates the average production of an economy and hence the allocation between "basic" goods and less materially-intensive (service-like) sectors. The basket of goods reflected by "GDP per Capita" approximates the synthesis of the different sectors of an economy much more satisfactorily than aggregate GDP. This is evident in the example of the two economies (see Table 1) with the same aggregate GDP but with substantially different populations, and hence GDP per Capita. The economy with the higher GDP per Capita, ceteris paribus, is more intensively oriented towards service-like goods; an orientation which cannot be reflected by the very same aggregate GDP of the two economies. The basket of goods whose monetary value is indicated by the GDP per Capita approximates the set, and especially the synthesis, of basic and service-like goods consumed by citizens. These goods should have certain properties in order to satisfy the needs of human beings. Hunger, thirst, transport, housing, etc., on one hand, and telecommunications, social media, and other services on the other hand, are all satisfied by a "basket" of goods whose monetary value is approximated by the "GDP per Capita" index. The physical properties of goods are indirectly traceable at the level of GDP per Capita, since the allocation of the aggregate production to different sectors is better approximated.

The actual contribution of the present analysis is the consideration of the economic process on the Human Scale, a consideration with implications for the evaluation of the Material Intensity of the economy. As human needs are the ultimate "*cause*", and human beings the ultimate "*causa-efficiente*", of the economic process, the outcome of the production process should therefore be envisioned on the *Human Scale*. The concept of "*human scale*" is widely used in social and environmental sciences (Gibson et al. 2007; Folke et al. 1996), and certain economic approaches use the "*human scale*" to analyze economic development (Cruz et al. 2009; Max-Neef 1991, 1992). However, although the human scale is relevant, it is largely neglected by studies of dematerialization and decoupling. The present research aims at evaluating the implications of the human scale on the material requirements of the production process. We thus define the proposed framework, as Human Scale Production (HSP), production that is directly related to the restrictions and limitations imposed by the bio-physical properties of the human scale on decoupling potentials (Bithas and Kalimeris 2016). By evaluating the MI of "GDP per Capita" the human scale enters the decoupling analysis. The present study proposes DMC/Income (where Income = GDP per Capita), as an alternative framework for evaluating the link between economic growth and natural resource use. The proposed indicator evaluates the resource requirement of an economic variable, GDP per Capita, that approximates the physiology of actual goods more successfully than GDP. DMC/Income can be seen as an evaluation of the Material Intensity that takes into account the effects and the constraints imposed by the human scale of production serving actual human needs (HSP). DMC/Income investigates the link between resources and production, once the production process is envisaged as taking place at the human scale, with the economy being an integral part of the actuality of Coupled Human and Natural Systems (CHANS). (Liu et al. 2007; Mavrommati et al. 2016).

The interest of this article lies in the comparison between the historical trends of the standard "**DMC/GDP**" and the proposed "**DMC/Income**" ratios. Since these indicators have different algebraic structures, their numerical values are by definition different and their comparison meaningless. However, the historical trajectory of the "materials required for the production of one unit of Income" reveals important aspects which are masked in the trajectory of the "materials required for the production of one unit of GDP". This comparison is the real essence of the present analysis and concerns the very essence of the economic variables incorporated in the two indicators which extend beyond their algebraic forms. DMC/GDP evaluates the MI of the average monetary unit, while DMC/Income the MI of one unit of income which approximates the utility provided by the set of goods consumed by the average individual. Indeed, this difference is essential.

The present study limits its scope to pure mass resources. The link between aggregate resources (mass and energy) and growth, as well as the link between energy and the economy have been sufficiently investigated in recent studies. However, the role of pure mass resources in the economic process has not hitherto attracted the interest of analysts, although mass resources play a distinct role since it provides the inputs necessary for the shaping the body, the material structure, the physical dimension of goods. The present study emphasizes the physical dimensions of goods, the physical properties with substantial implications for the requirements of mass resources. A house cannot be useful if it has the dimensions of a dollhouse; a car cannot be functional if it has the size of a toy car. The main assumption of the present study is that the satisfaction of human needs requires "*real world*" goods which, inevitably, have certain physical dimensions. The shaping of these physical dimensions requires substantial mass flows. The "cause" behind the physical dimensionality of economic production is the nature of human needs. The outcome of the economic process has certain physical dimensions determined by the "*human scale*" (Lawn 2001). Goods are embodied in certain physical forms, a "scaffold" that is constructed from mass inputs. Evidently, DMC_{mass} is not proposed as an alternative measure over DMC, but as a subcategory of DMC.

4 Data Overview

In order to confer a sense of comparability, the present study draws data[5] from Krausmann et al. (2009), one of the most up-to-date studies on global material intensity estimates. It also uses unpublished data kindly provided by the corresponding author of the aforementioned study, Prof. Dr. Fridolin Krausmann, following personal communication, in 2012.[6] The present study focuses exclusively on mass (non-fuel) inputs, for the period 1900–2009. As mass inputs (defined as World DMC_{mass}) we aggregate: non-fuel biomass;

[5] Data are available at: http://www.uni-klu.ac.at/socec/inhalt/1088.htm.

[6] We received disaggregated data on wood-fuel, as being the only available "fuel" part of biomass. In this context, we assume that data on wood fuel biomass is the only fuel part of aggregate biomass. However, our estimates may fail to trace the use of timber extraction and other agricultural by-products as fuel materials; consequently, there is a possibility of having underestimated the real fuel biomass quantity. For more details concerning the way that aggregate biomass has been estimated, see Krausmann et al. (2009).

ores-industrial minerals; and construction minerals. In this context, the equation between the time series of the World DMC, estimated by Krausmann et al. (2009), and the time series of the World DMC_{mass}, estimated by the present study, can be summarized as:

$$\begin{aligned}[\text{World } DMC_{mass}]\ ti &= [\text{World DMC}]\ ti \\ &- [\text{all energy carrier materials (oil; coal; and natural gas)}]\ ti \\ &- [\text{wood-fuel biomass}]\ ti\end{aligned} \quad (1)$$

with i taking values between the time (t) period 1900–2009.

In order to capture only the non-fuel biomass in our estimates, we have excluded fuel biomass, wood-fuel in particular, from the total aggregate biomass time series. DMC_{mass} is expressed in 1000 metric tons per year (1000 t/yr).

Data on GDP and population are drawn from Maddison (2003, 2008).[7] The GDP is measured in millions of 1990 International Geary-Khamis US$[8] per year. Population is expressed in millions of persons per year.

5 Analysis and Results

5.1 The Global Aggregate MI_{mass}

Figure 1 depicts the decoupling estimates of the World "DMC_{mass}/GDP" ratio and the World "DMC_{mass}/Income" ratio, both indexed to a base year (1900 = 1), for the period 1900–2009. The World DMC_{mass}/GDP ratio follows a steep decoupling trend throughout the period examined. A few brief interruptions occur from 1921 to 1930 (post-WWII period and economic recession of 1929); from 1932 to 1942 (pre-WWII period and outbreak of WWII); and from 1945 to 1950 (post-WWII period). An uninterrupted declining trend is observed during the 1950–2000 period. Finally, the period 2000–2009 is characterized by stabilization of the World DMC_{mass}/GDP.

In contrast, the World DMC_{mass}/Income ratio, reflecting the proposed evaluation framework, depicts a macro-coupling relation for most of the period examined (Fig. 1). Specifically, a period of relative stability occurs from 1900 to 1921, followed by some minor fluctuations from 1922 to 1950. From 1951 onwards, material intensity increases steadily until 2009, with only some brief interruptions occurring during the 1990–1992 period. Notably, the recent 2000–2009 period is characterized by an accelerating coupling trend.

5.2 Disaggregating Mass Resources: Ores-Industrial Minerals; Construction Minerals; Non-fuel Biomass

In this section we disaggregate World DMC_{mass} into three major and distinct mass forms: ores-industrial minerals; construction minerals; and non-fuel biomass (Krausmann et al. 2009). Material intensity is estimated separately for each category.

[7] Data available at: http://www.ggdc.net/MADDISON/oriindex.htm.

[8] The International Geary-Khamis dollar is a hypothetical unit of currency that has the same purchasing power as that of the 1990 United States dollar in the USA.

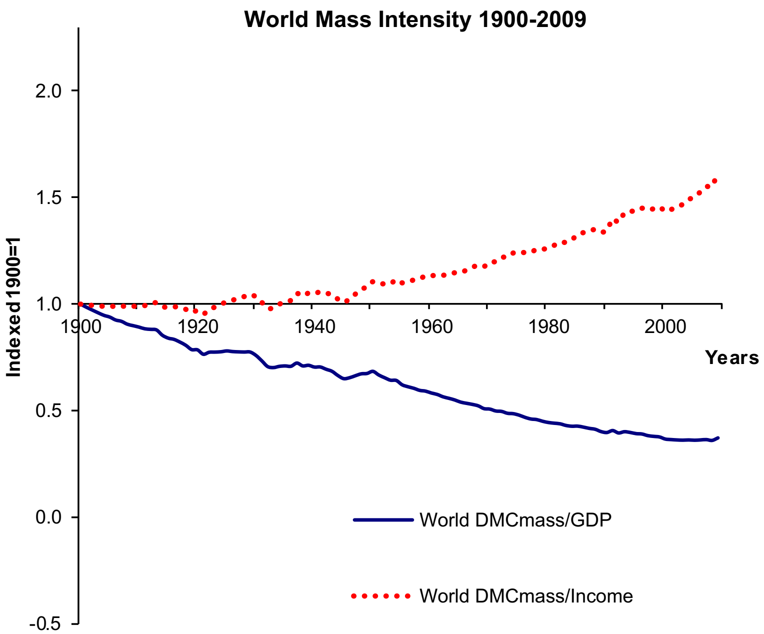

Fig. 1 The world DMC_{mass}/GDP and world DMC_{mass}/Income ratios for 1900–2009, all indexed (1900 = 1). World DMC_{mass} is the aggregation of ores, industrial minerals, construction minerals, and non-fuel biomass. *Data source* Krausmann et al. (2009) and personal communication

5.2.1 Trends of the Relative use of Individual Mass Inputs

Before estimating decoupling ratios for individual mass forms, Fig. 2 demonstrates the trends in their relative use as a proportion (%) of the world's total mass resources (DMC_{mass}). At the beginning of the period under examination (1900), global aggregate mass supply stood at 5.6 billion tons per year, out of which 84.5 % was the share of non-fuel biomass. Ores-industrial minerals and construction minerals accounted for 3.7 and 11.8 %, respectively. Non-fuel biomass followed a steady decline until 1913. This trend is reversed during WWI, where non-fuel biomass increased from 79.8 % in 1913 to 82.7 % in 1919, while ores-industrial and construction minerals showed a smooth decline (from 5.8 and 14.4 % in 1913 to 4.5 and 12.8 % in 1919, respectively).

After WWI, non-fuel biomass declined again until the recession of 1929–1933. In the meantime, the contributions of ores-industrial and construction minerals continued increasing until 1929. The great depression (1929–1933) marked once again an increase in non-fuel biomass use (from 75.8 % in 1929 to 79.8 % in 1933), while the use of ores-industrial and construction minerals declined in the same period (from 7.1 and 17.1 % in 1929 to 4.1 and 16.1 % in 1933, respectively). From 1933 on, non-fuel biomass use (79.9 %) declined continuously until 1940 (73.9 %). It was accompanied by a corresponding increase in the use of ores-industrial minerals (from 4 % in 1933 to 7.8 % in 1940), and construction minerals (from 16 to 18.3 %, during 1933–1940). The WWII period (1940–1945) marked the last peak in the relative use of non-fuel biomass (76.4 % in 1945) while the contributions of ores-industrial and construction minerals declined from 7.8 and 18.3 % in 1940 to 6.3 and 17.3 % in 1945, respectively. The year 1945 constituted

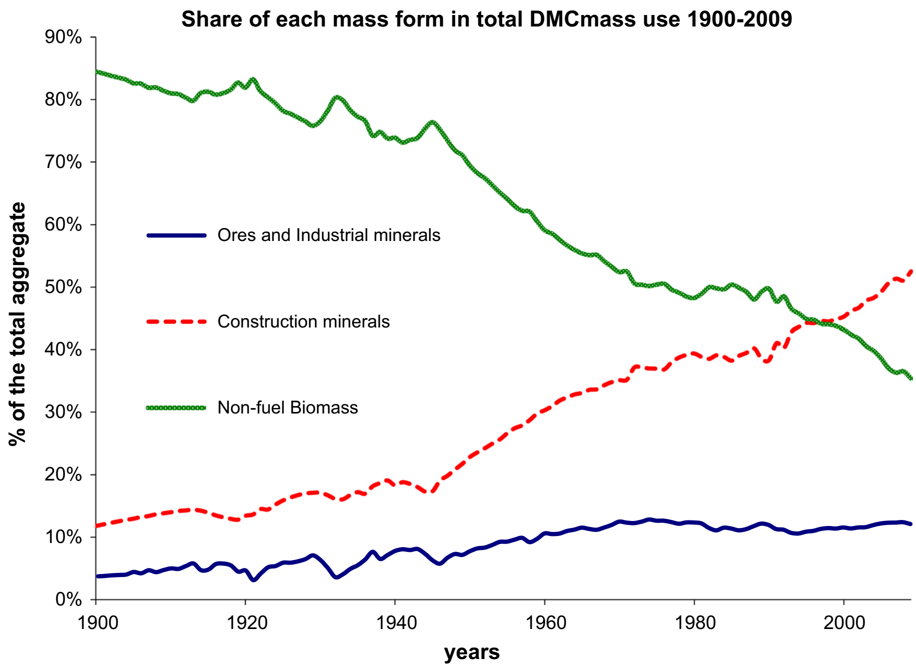

Fig. 2 Share of mass forms in (%) of world total DMCmass use, estimated for ores and industrial minerals, construction minerals, and non-fuel biomass for 1900–2009. *Data source* Krausmann et al. (2009) and personal communication

a turning point, marking the start of a long period in which the share of non-fuel biomass followed a sharp and continuous decline, while construction minerals sharply increased their contribution to total mass flows; Ores-industrial minerals presented a slower increase compared to construction minerals. These trends continued uninterrupted until 1972, the early phase of the first oil crisis. During the 1972–1976 period stabilization occurred with biomass varying around 50.3 %, ores-industrial minerals 12.5 %, and construction minerals 36.5 %. After 1976, non-fuel biomass decreased steadily whereas construction minerals increased sharply. Ores and industrial minerals remained rather stable after 1976. The year 1997 was the next milestone as construction minerals took the lion's share (44.6 %), a situation which continued uninterrupted until 2009, reaching 52.5 % of total DMC_{mass}, while the non-fuel biomass contribution fell back to 33.5 % (2009). Ores-industrial minerals displayed a relatively steady contribution to the share of total DMC_{mass}, fluctuating between 10.5 and 12.5 % for most of the period 1976–2009.

The historical trends in the use of renewable and nonrenewable (mass) resources arise as an important issue in recent economic history. Renewable non-fuel biomass has been gradually replaced with non-renewable ores-industrial and construction minerals during 1900–2009. Non-fuel biomass which stood at 76.4 % in 1945 presented declining use until 1973 (50.4 %), while non-renewable resources showed a sharp increase during the same period (from 23.6 % in 1945 to 49.6 % in 1973). After 1986, non-renewable materials took the lion's share in total DMC_{mass} (from 50.1 % in 1986 to 64.6 % in 2009), while the share of renewable mass resources (non-fuel biomass) declined continuously from 49.2 % in 1986 to 35.4 % in 2009. The relevant trends are presented in Table 2.

Table 2 Changes in the composition of renewable and non-renewable mass resources for selected years (expressed in % of the world DMC_{mass})

Year	Renewable mass flows[a] (%)	Non-renewable mass flows[b] (%)
1900	84.5	15.5
1945	76.4	23.6
1973	50.4	49.6
1986	49.9	50.1
2009	35.4	64.6

[a] Non-fuel biomass

[b] Ores-industrial and construction minerals

5.2.2 MI Estimates of Individual Mass Inputs

Figure 3a–c present the world "Ores-Industrial Minerals/GDP" and the world "Ores-Industrial Minerals/Income"; the world "Construction Minerals/GDP" and the world "Construction Minerals/Income"; and the world "non-fuel Biomass/GDP" and the world "non-fuel Biomass/Income", respectively. All estimated indicators are indexed (1900 = 1).

The "*Ores-Industrial Minerals/GDP ratio*" (Fig. 3a) presents three sharp decoupling periods: 1913–1921 (WWI and the early post-WWI period); 1929–1933 (The Great Depression); and 1941–1946 (WWII and the early post-WWII period). From 1946 on, the ratio gradually follows an increasing trend until 1970, when it peaks at its highest level of the whole period examined. Eventually, Material Intensity (MI) of ores and industrial minerals gradually declines for most of 1971–1994. From 1995 to 2009, the "*Ores-Industrial Minerals/GDP ratio*" seems to stabilize, showing a hint of a marginal increase between 2001 and 2009. A rather different evolutionary pattern characterizes the "*Ores-Industrial Minerals/Income*" (Fig. 3a) which depicts the same dematerialization periods (WWI; the Great Depression; and WWII), albeit not as sharply as depicted in the "*Ores-Industrial Minerals/GDP ratio*" trajectory. However, from 1946 to 1974, the "*Ores-Industrial Minerals/Income*" ratio shows a sharp increase in material intensity. The fluctuations observed from 1975 to 1994 are again followed by a sharp increase in material intensity from 1994 to 2009.

The "*Construction Minerals/GDP*" ratio (Fig. 3b) results in three dematerialization periods: 1913–1919 (WWI); 1929–1933 (the Great Depression); and 1939–1945 (WWII). From 1945 to 1960, "*Construction Minerals/GDP*" increases sharply, settling into a period of relative stability from 1960 to 1980, followed by a brief period of decline from 1980 to 2000, and sharply increasing again in the 2000–2009 period. The "*Construction Minerals/Income*" ratio (Fig. 3b) presents a relative stability with smooth fluctuations from 1900 to 1945. After 1945 and until 2009, the ratio depicts a constant coupling relationship between construction minerals and Income, marginally interrupted during the 1988–1992 period.

The "*Non-fuel Biomass/GDP*" ratio indicates a constant biomass intensity decline during 1900–2009 (Fig. 3c). Two periods may be identified: 1900–1980 which results in firm decoupling; and 1981–2009 when moderate decoupling is observed. On the other hand, the "*Non-fuel Biomass/Income*" ratio indicates a prolonged period of relative steadiness for the period 1900–1950. A sharp biomass intensity decline is observed during 1951–1966, followed by a period of fluctuating intensity from 1967 to 1980. Again, the period 1980–1992 shows increasing non-fuel biomass intensity, followed by a brief decline during 1993–2006. Finally, the period 2006–2009 hints at a marginal increase of non-fuel biomass intensity.

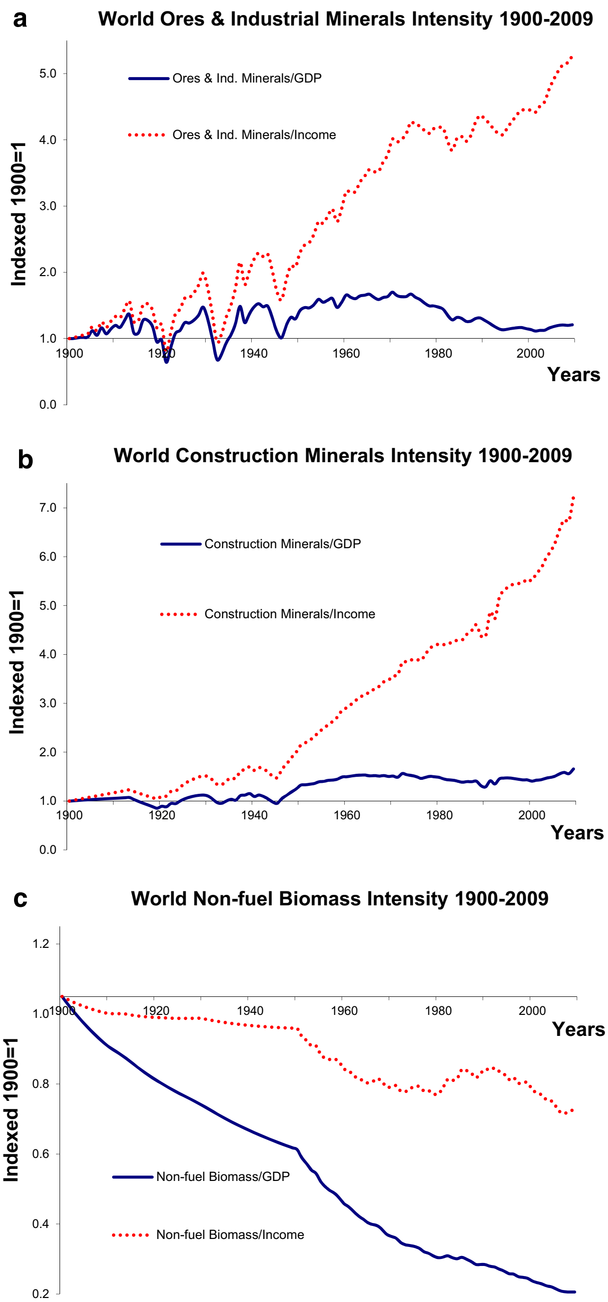

Fig. 3 Disaggregated mass resources. **a** World Ores and Industrial Minerals/GDP and World Ores and Industrial Minerals/Income ratios; **b** World Construction Minerals/GDP and World Construction Minerals/Income ratios; **c** World non-fuel Biomass/GDP and World non-fuel Biomass/Income ratios, all indexed (1900 = 1), estimated for 1900–2009. *Data source* Krausmann et al. (2009) and personal communication

5.3 The Evaluation of Decoupling Index (DI) for World DMC_{mass}/GDP and World DMC_{mass}/Income

The present section evaluates the Decoupling Index (DI) proposed by UNEP (2011). DI evaluates the sensitivity of GDP to the changes in natural resource use, defined as the elasticity of GDP to the natural resource inputs. As proposed by Bithas and Kalimeris (2013), in order to smooth out short-term fluctuations of the economic cycles we estimate a time period of one decade instead of the proposed one-year period, by using moving averages per decade:

First, we estimate the DI for the standard DMC_{mass}/GDP ratio:

$$\frac{(DMC_{mass_t} - DMC_{mass_{t-1}})/DMC_{mass_{t-1}}}{(GDP_t - GDP_{t-1})/GDP_{t-1}} = \frac{\Delta(DMC_{mass})}{\Delta(GDP)} \tag{2}$$

where t is an averaged time period of one decade. Hence, $t-1$ represents the change from the average of one decade to the next. Secondly, we estimate the DI for DMC_{mass}/Income, using the same formula but with GDP replaced by GDP per Capita throughout.

DI is interpreted as follows (UNEP 2011):

- $DI > 1$: there is coupling between the two variables examined.
- $DI = 1$ is the turning point between coupling and relative decoupling.
- $0 < DI < 1$: relative decoupling is taking place.
- $DI = 0$ indicates that the economy is growing while resource consumption remains constant. This is the turning point between relative and absolute decoupling.
- $DI < 0$: the relationship can be described as absolute decoupling.

Figure 4 displays estimates of the DI for the standard world DMC_{mass}/GDP and the proposed world DMC_{mass}/Income (indexed decade 1900 = 1). As far as the standard DMC_{mass}/GDP is concerned, DI results in a prolonged relative decoupling throughout the whole period examined, with values between 0.5 and 0.7, always <1. In contrast, the DI of the proposed DMC_{mass}/Income indicator, with the exception of a smooth relative decoupling period (1910 decade: 1910–1919, where $DI = 0.96 \approx 1$), results in a constant coupling, with values above 1 which represents the borderline between coupling and relative decoupling. Evidently, the elasticities estimated by DI further support fundamentally different trajectories for the two indicators.

6 Discussion

The empirical estimates indicate that the "*mass inputs required for the production of a unit of GDP*" follow fundamentally different trends from the "*mass inputs required for the production of one unit of Income*". DMC_{mass}/GDP follows a decoupling trend which strongly supports the dematerialization of the economy. In contrast, the DMC_{mass}/Income supports a strong linkage between Income and mass inputs, and therefore a dependency of the economic process on mass resources. This dependency is clearly depicted in the estimates of individual mass inputs as the findings indicate a stronger link between growth and those resources with increasing relative share. This conclusion is clearly supported by both MI indicators. Specifically, the use of construction materials is coupled with growth for both ratios, though more intensively for "*Construction minerals/Income*", as construction materials increase their share in total material use. The same holds true for ores

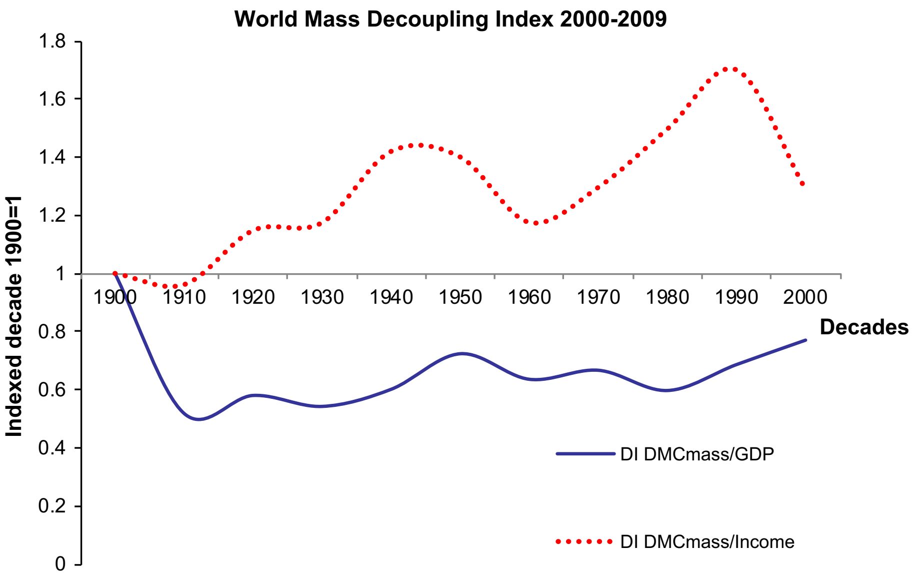

Fig. 4 The estimation of the decoupling index (DI) for the standard world DMC_{mass}/GDP and the proposed world DMC_{mass}/Income for 1900–2009 (indexed decade 1900 = 1)

and industrial minerals. On the contrary, the decoupling trends for non-fuel biomass intensify as the use of non-fuel biomass shrinks. Specifically, for the period 1950–1966 when the non-fuel biomass contribution declined from 69.4 % in 1950 to 55.1 % in 1966, both "*Non-fuel Biomass/GDP"* and "*Non-fuel Biomass/Income*" ratios (Fig. 3c) indicate a sharp reduction of biomass intensity. Similarly, the strong decoupling periods (WWI, the Great Depression, and WWII) of ores-industrial minerals and construction minerals (Fig. 3a, b, respectively), are accompanied by a decrease of their shares in total material use.

Evidently, decoupling of each individual mass flow occurs mainly when its share in total mass resources (DMC_{mass}) shrinks, while the periods of its increasing relative use are characterized by stronger coupling with growth.

Remarkably, estimates of Material Intensity (MI_{mass}) for individual mass inputs are revealing with regard to the structural changes in the link between the economy and resources during periods of socioeconomic crisis. Indeed, during periods of uncertainty (wartime and economic recessions), the socioeconomic process depends more intensively on those resources which are more easily accessible. Indeed, easily accessible biomass increases its relative share during crises. Notably, although the relevant impacts are reflected by both indicators, the DMC_{mass}/Income index more clearly approximates the particular characteristics of the dependency of the economic process on those resources more easily accessible during wartime and periods of extreme recessions. These extraordinary events result in changes in the way human needs are satisfied, with implications for the MI of the economy. These impacts are better approximated by the proposed indicator, which is sensitive to the structure of the economy.

The empirical analysis also indicates a macro-trend concerning the relative share of renewable-nonrenewable resources and the respective material intensities. Throughout the period with available data, nonrenewable resources are constantly increasing their use relative to renewable ones (non-fuel biomass). This trend results in a major landmark in the mid-1980s, when nonrenewable mass inputs became predominant. The sheer reduction in the share of renewable mass inputs is associated with a clear decoupling confirmed by both indicators. On the other hand, the constantly increasing relative share of nonrenewable resources is accompanied by a strong link between their use and the economic process, a finding supported by both decoupling indicators, notably, far more intensely by the DMC_{mass}/Income ratio.

7 Conclusions

Does "matter" matter in economic growth? The paper attempts to answer this question by estimating the historical dependency of production on mass inputs. Towards this objective, the paper compares empirical estimates following the standard MI evaluation framework (DMC_{mass}/GDP) with estimates based on the DMC_{mass}/Income index reflecting the framework proposed by the present study. The differences in the historical trajectories are interpreted through a bio-economic approximation of the production process. The world DMC_{mass}/GDP follows a decreasing path throughout the economic history of the period 1900–2009. This prevailing trend, once combined with unparalleled technological advance, may well raise optimism for a transition to an era of the relative dematerialization of the economic process and substantial independence from material resources. This reasoning is based on considerations of the economy at the level of aggregate GDP, the highest level of monetary aggregation. Envisaging the economy at the aggregate level deprives the production process of any correspondence to its physical properties. Goods are transformed into a monetary amalgam and then, the creation of one monetary unit can be envisaged to require infinitesimal material inputs.

However, real world goods embody certain bio-physical properties in order to satisfy human needs. The implications and limitations imposed by the physical properties of real-world goods in the evaluation of the link between the economy and resources ought to be taken into account. Human needs are the "*cause*" of production since human beings are the "*causa-efficiente*" of the economic process. The actual properties of production can be traced once the production is envisioned on the human scale. GDP per Capita emerges as an index that reflects the Human Scale of Production (HSP) within the monetary domain, as approximates a more tangible set of goods, denoted as the average income consumed by the representative citizen. The physical properties of production could be traced more effectively for the set of goods denoted by "GDP per Capita". Within the HSP framework, we propose the DMC/Income ratio as a better approximation of the actual MI of the production process. Empirical estimates of the world DMC_{mass}/Income indicate increasing MI_{mass} after 1950 and up to 2009. Contemporary economic growth requires disproportionate increments in mass inputs. The economic process remains dependent on mass resources despite unparalleled technological advances.

DMC_{mass}/GDP and DMC_{mass}/Income indicators reflect two fundamentally different perceptions of the economic process, a difference that overcomes their numerical forms and concerns the very essence of the economy. If the economic process is perceived as an engine ultimately producing monetary units, then high expectations exist for dematerialization and for the consequent independence of natural resources. On the contrary, if the economic process is envisaged as a human scale process producing goods in order to serve the human needs of an increasing population then, although there might be some potential for decoupling due to technological progress and reconstruction of the economy, ultimately this potential is limited owing to the constraints imposed by the physical properties of real world goods and the population dynamics (Tepperman 1981). If the economic process is envisaged as an integral part of Coupled Human-Natural Systems (CHANS), then natural resources are a crucial and indispensable element for the economic process. This conclusion results in serious implications for the sustainability prospects of current growth rates and sheds new light on the growth-degrowth dialogue.

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