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ORIGINAL PAPER

Matter Matters: Reconsidering the (De)materialization of a Hundred Years of Growth

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Abstract
The present study attempts an empirical evaluation of the dependency of economic growth on mass resources. The distinct role of mass (non-energy) resources in the production process is investigated. We attempt a methodological contribution by delineating an improved approximation of the economy's ultimate outcome in the evaluation of the resource intensity. Remaining within the monetary realm, the income index is adopted as the appropriate indicator for the ultimate outcome of the economic system and, hence, the material requirements for producing one unit of income determine the actual dependency of the economy on resources. Our empirical analysis focuses on the historical trajectories of the link between mass resources and the economy over approximately the last 100 years, a period of tremendous growth rates and efficiency gains induced by technological progress. Data availability restricts our analysis to the global economy, the USA and Japan. These are two national economies which have experienced technological miracles in the production process, and the re-orientation of their economies toward knowledge-based sectors. Our findings indicate an increasing dependency of the global economy on mass resources throughout the period of available data (1900–2009). The 4.8-fold increase in global income led to a disproportionate 8.5-fold rise in mass flow. The USA and Japan initiated a decoupling trend in the mid 70's, after the strong coupling period that followed World War II. These estimates question the prevailing vision of "dematerialization" and cast doubts over the efficiency of current resource policies.

Keywords Decoupling · Dematerialization · Material intensity (MI) · Natural resource scarcity · Sustainable development · Economic welfare · Mass resources

Introduction

The intricate relationship between natural resources and the economic process has renewed the interest of empirical studies, fueled by datasets developed in the context of Material Flow Analysis (MFA), a widely used framework for the investigation of the link between the economy and resources (Bringezu et al. 2003; Fischer-Kowalski et al. 2011; Efthimiou et al. 2017; Bithas and Kalimeris 2018). MFA supports the development of a wide range of methods, indexes, and standardized databases concerning the physical aspects of global and national economies and hence feeds a huge volume of scientific literature and policy reports by international organizations (OECD 2004; Eurostat 2009; EEA 2012; UNEP 2011; Eurostat and OECD 2012).

Material intensity (hereinafter MI) has been adopted as the pivotal variable for identifying the dependency of the economy on resources within the framework set by MFA. MI is defined as the amount of resources required to produce one unit of GDP, denoted by the ratio Domestic Material Consumption (DMC)/GDP.[1] Empirical estimates suggest a declining MI, a decreasing amount of resources required for

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[1] Where Domestic Material Consumption (DMC) = Domestic Extraction (DE) + Material Imports – Material Exports.

one unit of GDP for the global economy, as well as for the vast majority of national economies throughout the periods with available data. This is the so-called "decoupling effect," a phenomenon which induces optimism for sustainable development and green growth (Schandl et al. 2016; Hatfield-Dodds et al. 2017; Szigeti et al. 2017) with substantial influence over resource policy at the global and national level.

Decoupling research focuses either on aggregate resources (such as the DMC indicator) or exclusively on energy flows. The distinct evaluation of mass (non-energy carrier) resources has escaped the scrutiny of the recent decoupling analyses. Disaggregating resources offers an opportunity to investigate specific aspects of the Resources-Economy (R-E) link (i.e., for the role of Oil extraction in economic growth see: Aude and Schindler 2017). Energy resources provide power for the production process, while mass resources are transformed into material substance, the skeleton of goods (Schaffartzik et al. 2016). The present study examines the link between pure mass flows and economic growth. Pure mass resources are defined as the subcategory of total DMC once energy resources have been subtracted; mass flows are denoted, hereafter, as *Mass* Domestic Material Consumption (DMC_{mass})[2] the key resource variable of our empirical analysis. A standard analysis would evaluate the link between mass and growth through the ratio of mass resources consumed for producing one unit of GDP (DMC_{mass}/GDP), defining the Mass Intensity (MI_{mass}) of the economy. The present study wishes to contribute at the methodological level and to shed some new light on the R-E link by estimating the amount of mass resources required for the production of one unit of $GDP_{per\ capita}$, one unit of income. We argue that $GDP_{per\ capita}$, is the appropriate monetary indicator for approximating, in monetary terms, the ultimate outcome of the economy. The economy serves the needs of human beings and creates economic utility. The number of human beings embedded in an economy matters. As population changes across countries and time, economies of the same aggregate GDP may be fundamentally different, as they provide different utility levels to their individuals. A simple comparison between indicative countries suffices to support this. For example, India and Japan shared almost the same level of aggregate GDP from 2001 to 2006, whilst the USA shares comparable levels of aggregate GDP with China since 2005.[3] However, the tremendous difference in population size between these countries results in extremely different levels of $GDP_{per\ capita}$ indicating the divergent utility enjoyed by individuals in these countries, a fact which undoubtedly suggests different structures for these economies. Economic theory has adopted the index of $GDP_{per\ capita}$ as an appropriate monetary measure of the economic utility enjoyed by human beings (Kaldor 1939; Hicks 1939; Pigou 1951; Samuelson 1950). Accordingly, international organizations adopted $GDP_{per\ capita}$ as the major indicator for classifying economies, with the distinction between developed and developing economies a key classification indicating the utility level enjoyed by human beings in different countries.

GDP has been inadvertently adopted to report the performance of an economy since changes in population size are very slow compared to those of GDP, and hence GDP trends closely follow the trends of $GDP_{per\ capita}$. Nevertheless, GDP-based estimates may be misleading when historical, long run, periods are examined and when countries with different population levels are compared. This reasoning prompts the present study to propose $GDP_{per\ capita}$, the Income index, as the appropriate monetary aggregation level for the evaluation of the link between the economy and resources. The resulting estimates incorporate the structure of the economy, which is irrevocably prescribed by the number of people embedded within it. The economic process is an integral component of the Coupled Human and Natural Systems—CHANS, (Liu et al. 2015), serving the needs of human beings, and hence population size matters.

The $GDP_{per\ capita}$ index has a long history in the literature of environmental economics, with the Environmental Kuznets Curves holding a predominant position (Panayotou 1997; Stern 2004; Bampatsou et al. 2017). In addition, the causal relationship between energy and growth has been investigated on the basis of "$GDP_{per\ capita}$" (Soytas and Sari 2003, 2006; Lee 2006; Huang et al. 2008; Kalimeris et al. 2014), while "$GDP_{per\ capita}$" has been used for the evaluation of the energy and the CO_2 intensity of certain economies (Bithas and Kalimeris 2013, 2016; Salahuddin and Gow 2014).

In the present study, we estimate and compare the trends in the MI of mass resources (MI_{mass}) using both the DMC_{mass}/Income and the DMC_{mass}/GDP, for the global economy (1900–2009), the USA (1870–2005), and Japan (1878–2005). These two countries are gigantic, post-industrial, economies with an advanced technological status inducing the efficient use of material inputs and resulting in high expectations for decreasing MI trends. Decoupling expectations for the USA and Japan are further fueled by the restructuring of these economies towards the service sector and the outsourcing of industrial production to various developing countries.

[2] Where DMC_{mass} = Domestic mass extraction + mass (non-energy) Imports − mass (non-energy) Exports. All energy resources are extracted from our estimates (for the calculation method, see also Bithas and Kalimeris 2017). Furthermore, we have also excluded wood fuel from biomass (more details in the "Data sources").

[3] All comparisons are based on of International 1990 Geary–Khamis dollars. Source: The Conference Board Total Economy Database™, January 2014, http://www.conference-board.org/data/economydatabase/.

The Material Intensity of Growth: The Structure of the Economy and the Biophysical Properties of Goods

The MI of the Ultimate Outcome of the Economy

Efficiency in the use of resources ought to be evaluated at the boundaries of the economic system, by comparing the amount of resources entering the economy with its ultimate outcome. The ultimate outcome of the economy is welfare, the enjoyment of life, induced by the use of goods which are exchangeable through markets. The economy is an integral component of the Coupled Human and Natural Systems (CHANS) intended to serve human beings. The economic system produces goods to satisfy human needs, and thus creates economic welfare–utility. The enjoyment of economic welfare is an individualistic phenomenon and, therefore, economies of the same aggregate GDP (the same scale) provide substantially different welfare–utility, when different populations benefit from the very same GDP. This difference is reflected in the differences of the $GDP_{per\ capita}$ index. $GDP_{per\ capita}$ has been adopted as the standard index for the actual outcome of the economy. $GDP_{per\ capita}$ approximates, within the monetary context, the value of the economic welfare enjoyed by one human being, i.e., the value of the goods consumed by one citizen. This value is defined as the "*income*" available to each individual under conditions of equal distribution, reflecting an analytical abstraction. Income is the indicator widely used in international reports and statistics for comparing and classifying economies. Monetary-based indexes, such as GDP and $GDP_{per\ capita}$, are burdened by severe shortcomings, with the appropriate measurement of environmental externalities being an important one. Recent scientific initiatives aim at developing new indexes for an improved approximation of the actual utility enjoyed by human beings through addressing the shortcomings of monetary-based indexes. However, indexes such as the Index of Sustainable Economic Welfare (ISEW) and the Genuine Progress Indicator (GPI), to mention some indicative examples, are still in the research phase and the datasets available cover a limited number of economies over relatively short periods. Therefore, their empirical use still remains limited (Lawn 2005; Costanza et al. 2014). Under these constraints, the concept of income emerges as the readily available index encompassing the ultimate outcome of the economy. The present paper asserts that $GDP_{per\ capita}$ stands as the appropriate monetary aggregation for evaluating the MI of an economy and, therefore, the DMC/Income ratio is proposed as the appropriate indicator of MI. "*Resources required for the creation of one unit of income*" evaluates the efficiency of using resources in the economic process by comparing actual inputs (material flows) with actual outputs (economic welfare).

Table 1 Comparison of two substantially different economies which are treated equally by the standard MI index

	Economy A	Economy B
DMC	100,000	100,000
GDP	20,000	20,000
Population	5000	10,000
M = DMC/GDP	5	5
DMC/[$GDP_{per\ capita}$]	25,000	50,000
Income = $GDP_{per\ capita}$	4	2

The Population Size and the Structure of the Economy

Population size is among the driving forces of production and determines the relative shares of the economic sectors (Brooks and Andrews 1974; Sen 1979; Samuelson 1985). As population changes over time and across nations, economies with similar GDPs may produce different sets of goods. Evidence is offered by the causality of population size on the production of "*basic goods*." A larger population results, ceteris paribus, in a relatively larger demand for production of basic goods. The production of basic goods (dwellings, transportation, food, infrastructure, and so on) requires substantial material inputs, and thus implies a relatively stronger link between production and resource inputs. The implications of population size for the structure of the economic system are approximated by $GDP_{per\ capita}$, while they are completely ignored by aggregate GDP. The difference can be clearly reflected by a very simple numerical example. Economies A and B present the very same GDP and resource use (DMC). As a result, the standard MI of both economies is exactly the same, (Table 1), advocating an equal dependency on resources for A and B economies. Evidently, the two economies are substantially different in their structure of production, as Economy B serves double the population of Economy A. This is reflected in the $GDP_{per\ capita}$ index which is 2 in Economy B while it reaches up to 4 in Economy A. This indicates that the "*average*" individual in the two countries consumes a different bundle of goods. This fact results in the production of different goods, and, hence, different structures of the economic sectors, with Economy A being more strongly oriented towards service-like activities and B towards "basic" goods. The different structures of the two economies inevitably imply different requirements for resources. This is completely ignored by the standard MI estimates which are based on aggregate GDP and indicate exactly the same MI for both economies. The proposed indicator, DMC/[$GDP_{per\ capita}$], reflects the differences and indicates that Economy A is somehow more strongly oriented towards service-like goods which require fewer resources per unit of output.

Human Needs Determine the Biophysical Properties of Goods

The economic process is conditioned by physical laws and economic goods ought to encompass certain biophysical properties in order to be able to satisfy human needs. Human beings are the "*causa-efficiens*," i.e., the reason behind the economic process, and their needs determine the properties that goods ought to have in the actual world. The biophysical properties of goods determine their resource requirements and hence the resource intensity of the economy. The evaluation of the MI at the level of aggregate GDP obscures the implications and the limits imposed by the actual physical properties of goods since the aggregation of GDP makes no reference, even indirectly, to human beings who are in fact the "cause" of the economic process. GDP is the aggregate amalgam of monetary values of numerous goods; at that highest level of monetary aggregation the physical properties of goods are diluted and obscured. We suggest that the implications of the physical properties of production on the MI can be traced by downscaling the monetary value of GDP to the level of "$GDP_{per\ capita}$." The MI of "$GDP_{per\ capita}$" estimates the material requirements of the "*bundle of goods*" consumed by the "*average*" individual. Certain implications of the biophysical properties of the bundle of goods reflected by $\mathrm{GDP}_{\mathrm{per\ capita}}$ can be traced and certain constraints inherent in the actual production can be identified more effectively, at least when compared to the aggregate GDP. "$GDP_{per\ capita}$" denotes a monetary value with reference to the biophysical entity of human beings, the ultimate "*reason*" for the production process, which endows goods with certain biophysical characteristics. "$GDP_{per\ capita}$" brings the "*cause*" of the economic process, albeit indirectly, within the picture of MI evaluation and enriches it with properties reflecting the conditions in the actual world.

The Material Hypostasis of Goods and the Mass Requirements of Human Scale

The physical dimensions of goods constitute a fundamental biophysical property directly related to the nature of human beings and, thus, the human scale. Human beings through their needs determine the actual physical size that certain goods should have and set the threshold for the potential to "*shrink*" that size: a matchbox-sized car or an apartment of 2 m^2 would never be functional for human beings. In that sense, the physical scale of goods ought to serve the human scale, so the production of goods—compatible to the human scale—should be envisioned as a Human Scale Production (HSP); an economic production whose ultimate end is to serve the human needs, in respect to their biophysical properties and restrictions (Lawn 2001; Bithas and Kalimeris 2017). The mass requirements of the economic process are determined by the physical hypostasis, the physical dimensions, of the actual goods produced within an economy. The relevant implications can be more clearly reflected when the evaluation makes reference to the number of human beings sharing the production.

Data Sources

Pure mass resources are defined as total resource use minus energy resources, and therefore pure mass resources may be defined as non-energy carrier materials. Global mass (non-energy) materials consist of non-energy biomass, ores–industrial minerals, and construction minerals.[4] All data for ores–industrial minerals and construction minerals are drawn from Krausmann et al. (2009). Data on global non-energy biomass were obtained through personal communication.

$\mathrm{DMC}_{\mathrm{mass}}$ data for the USA and Japan are estimated as the aggregate of non-energy biomass, ores, and non-metallic (construction) minerals. Data on US ores and non-metallic (construction) minerals are drawn from Gierlinger and Krausmann (2011), and data on the US non-energy biomass from personal communication. Data on Japan's ores and non-metallic (construction) minerals are drawn from Krausmann et al. (2011), and data on Japanese non-energy biomass from personal communication. Published data are available online at: http://www.uni-klu.ac.at/socec/inhalt/1088.htm. Data on GDP and population are drawn from Maddison (2008: data available online at: http://www.ggdc.net/MADDISON/oriindex.htm).

Materials are measured in thousands of metric tons per year (1000 t/year).[5] Economic growth is expressed in terms of GDP in millions of 1990 International Geary–Khamis

[4] It is assumed that data on non-energy biomass is the only fuel/energy part of total biomass. However, the present article's estimates fail to incorporate the use of timber extraction and other agricultural by-products, as well as the so-called biofuel production. Consequently, according to the databases employed for the global economy, the USA and Japan, it is quite likely that the real fuel-biomass quantity has been significantly underestimated. In any case, the authors did not aspire to make any additional estimates concerning the biofuel proportion of total biomass over and above the data kindly provided by the constructors of the databases utilized.

[5] Metric ton is the unit of mass equaling 1000 kg, equivalent to 2204.62 pounds (Cleveland and Morris 2009, p. 326).

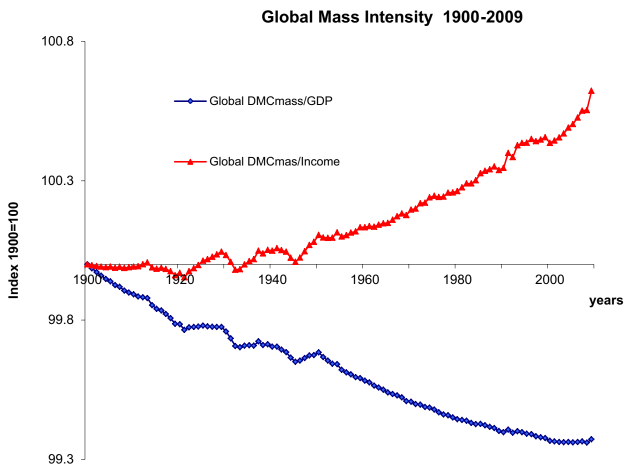

Fig. 1 Global DMC_{mass}/GDP and DMC_{mass}/Income ratios for 1900–2009, (indexed as 1900 = 100) (reconstruction of figure based on estimates by Bithas and Kalimeris 2017)

dollars per year (million 1990 PPP $/year).[6] Population is expressed in millions of persons per year.

Analysis and Results

The Global Economy: The Global Aggregate MI_{mass} for 1900–2009

Global mass consumption (hereinafter global DMC_{mass}) consists of the aggregation of ores–industrial minerals, construction minerals, and non-energy biomass. Figure 1 shows the evolutionary paths of global DMC_{mass}/GDP and the global DMC_{mass}/Income ratios indexed to 1900 as the base year (1900 = 100). The global DMC_{mass}/GDP is clearly characterized by a permanent decoupling trend. DMC_{mass}/GDP decreased constantly from 1900 to 1920; 1921–1950 is characterized by mixed trends, with short intervals of relative stability in periods with idiosyncratic historical characteristics: the economic recession and WWII. 1950 sets a milestone as it marks the beginning of a steady long-term decrease in MI_{mass} lasting until 2000. Finally, relative stability is observed from 2001 to 2009. Overall the long-term trajectories of DMC_{mass}/GDP result in a decrease of 35% from 1900 to 1945, and 46.4% from 1950 until 2000 (Table 2).

The global DMC_{mass}/Income evolves in stark contrast to the DMC_{mass}/GDP (Fig. 1). The first half of the twentieth century is characterized by a fluctuating stability, while an increasing coupling trend prevails after the 1950s. Indeed, the year 1950 constitutes once again a milestone for MI_{mass}, estimated by DMC_{mass}/Income, as it initiates a protracted period of increase until 2009, amounting to 46.7% (1950–2009). Remarkably, the period 2000–2009 is characterized by an accelerating increase of 13%, suggesting an intensive materialization of global growth in more recent years.

[6] 1990 international Geary–Khamis dollars are purchasing power parities (PPPs) used in evaluating output. They are calculated based on a specific method devised to define international prices. Information on the computation of the PPPs in Geary–Khamis dollars is available at http://unstats.un.org/unsd/methods/icp/ipc7_htm.htm.

Table 2 Estimates in indicative periods for global DMC_{mass}/GDP and DMC_{mass}/Income

Period	DMC_{mass}/GDP (%)	DMC_{mass}/ Income (%)
1900–1945	−35	0.9
1950–2000	−46.4	29.9
2000–2009	1.5	13
1900–2009	**−62.8**	**62.3**

Clearly, the DMC_{mass}/Income ratio showcases a substantially different evolutionary path in comparison to the DMC_{mass}/GDP over the last 100 years characterized by unprecedented growth rates and technological advances. DMC_{mass}/Income increased by 62.3% from 1900 to 2009, a fact which clearly indicates that income, at the global level, cannot increase unless mass input also increases at a disproportionate rate. The global economy is being "*materialized*," a trend with crucial implications concerning the dependency of the economic system on natural resources (Bithas and Kalimeris 2017, 2018).

The US Economy

MI_{mass} of the USA for 1870–2005

The USA is a typical example of a highly developed nation with advanced technology and an orientation of the production towards "*dematerialized*" sectors such as finance and services. Expectations of intensive decoupling are valid in the case of the USA.

The DMC_{mass}/GDP ratio shows a gradual dematerialization of the US economy, throughout the period with data availability, resulting in an overall reduction of 80% (1870–2005) (see Fig. 2; Table 3). Based on the trends of DMC_{mass}/GDP, the US economy has been substantially relaxing its dependency on mass resources. In contrast, the DMC_{mass}/Income ratio indicates a coupling trend for 1870–1976 with only a brief decoupling spell during WWII. The drastically increasing $GDP_{per\ Capita}$ by 594% required an increase of mass flow by 1171%, for 1870–1976. After 1976, the DMC_{mass}/Income ratio presents a decoupling trend, suggesting that the restructuring of the economy towards "*services*," technological efficiency, and outsourcing

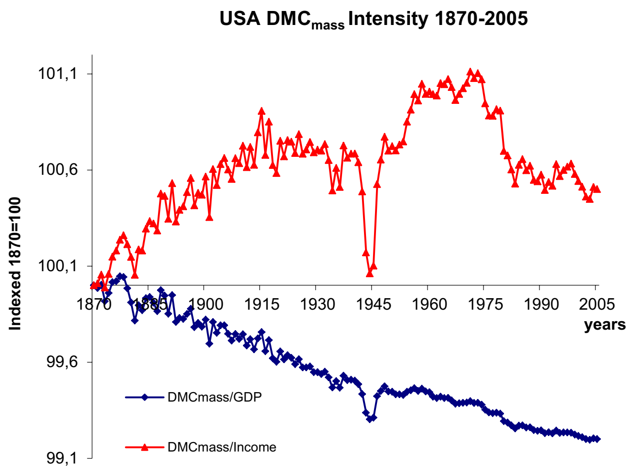

Fig. 2 USA's. DMC_{mass}/GDP and DMC_{mass}/Income ratios in 1870–2005 (indexed as 1870 = 100)

Table 3 Estimates in indicative periods for the USA's DMC_{mass}/GDP and DMC_{mass}/Income

Period	DMC_{mass}/GDP (%)	DMC_{mass}/ Income (%)
1870–1945	−68.9	10.2
1945–1973	24.9	90.9
1973–2005	−48.6	-28.7
1870–2005	**−80**	**49.9**

induced actual "*dematerialization*." The overall performance of DMC_{mass}/Income portrays an increase of 49.9% for 1870–2005 (Table 3).

Disaggregate USA MI_{mass} for 1870–2005

We evaluate MI for the three sub-categories of mass resources: ores, non-metallic minerals, non-energy biomass whose relative trends are depicted in Fig. 3a–c.

Two general conclusions can be drawn. First the DMC_{mass}/Income indicator suggests a stronger link between individual mass resources and the economy compared to that defined through the DMC_{mass}/GDP ratio. Second, this link emerges stronger for those materials whose relative use is increasing, while decoupling is evident mainly for those materials whose use is shrinking (Fig. 4).

As Fig. 3 demonstrates, the drastically increasing "$DMC_{non\text{-}metallic\ min}$/*Income*" ratio between 1950 and 1970 is in contrast to "$DMC_{non\text{-}metallic\ min}$/*GDP*" which emerges as stable in a period where "*non-metallic minerals*" increased substantially their relative share of the total mass resources (Fig. 3b).

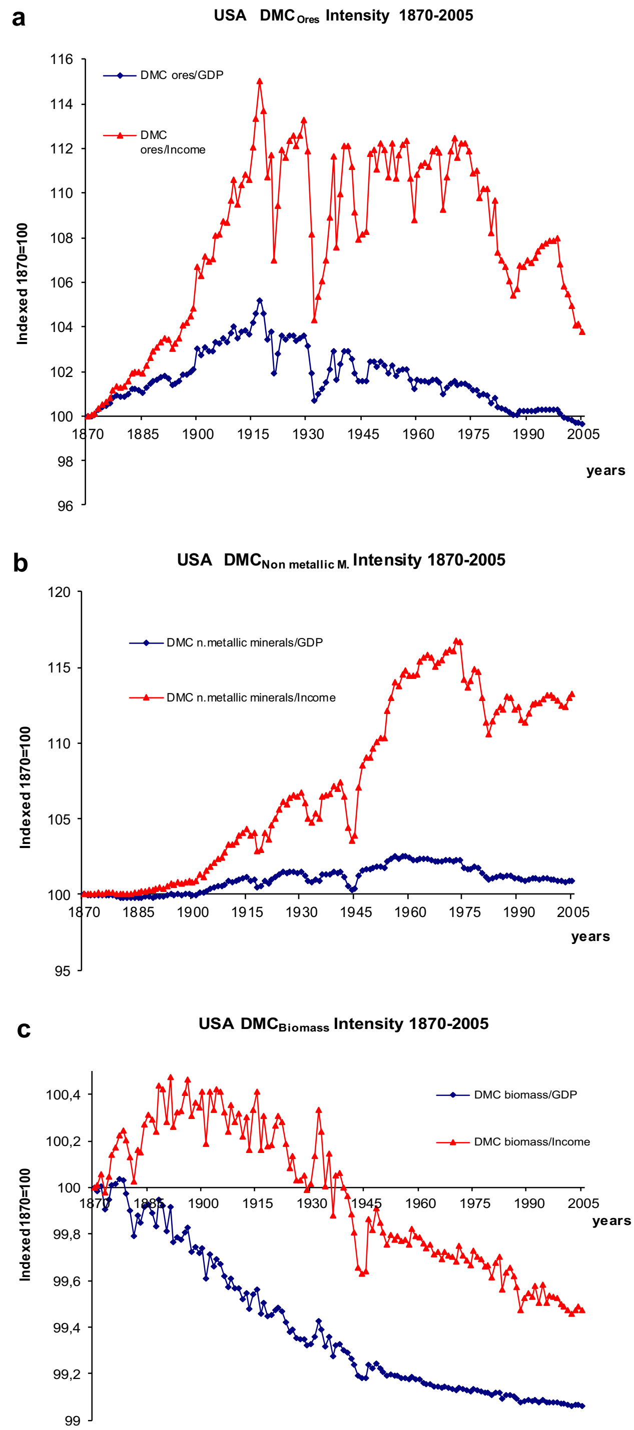

Fig. 3 **a** DMC_{ores}/GDP and DMC_{ores}/Income; **b** $DMC_{non\text{-}metallic\ min}$/GDP and $DMC_{non\text{-}metallic\ min}$/Income; **c** $DMC_{biomass}$/GDP and $DMC_{biomass}$/Income, for the period 1870–2005 (indexed 1870 = 100)

The DMC_{ores}/GDP decreases after WWII while the DMC_{ores}/Income increases until the 1980s (Fig. 3a). Remarkably, the $DMC_{biomass}$/Income ratio remains relatively stable

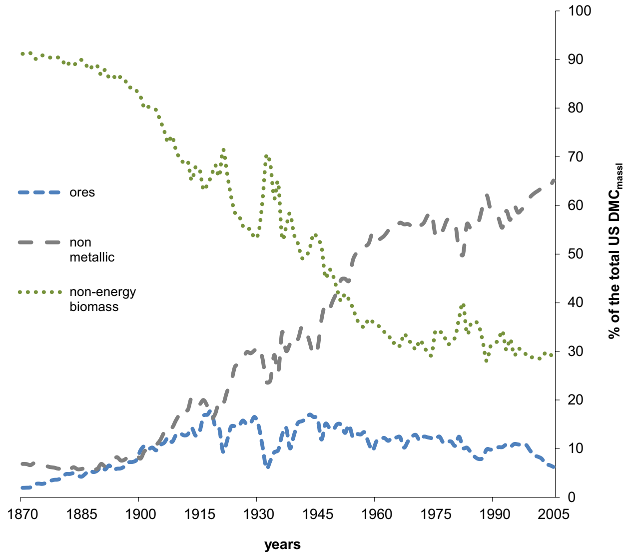

Fig. 4 Relative composition of the US DMC_{mass} (%) during 1870–2005

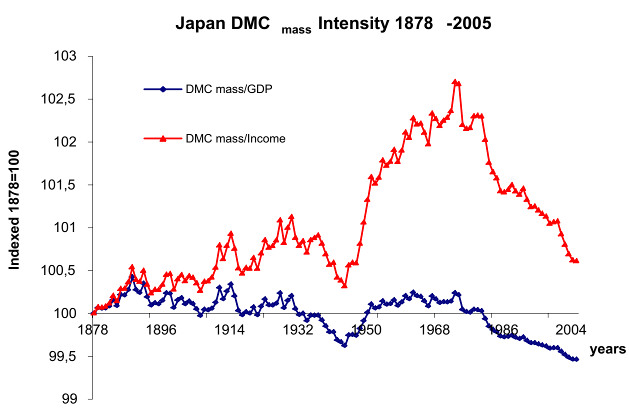

Fig. 5 Japan's DMC_{mass}/GDP and DMC_{mass}/Income ratios in 1878–2005 (indexed 1878 = 100)

until the end of WWII (Fig. 3c), then initiates a declining path as its relative share is also shrinking (Fig. 4).

The Japanese Economy

Japan's MI_{mass} for 1878–2005

Figure 5 compares the trajectories of DMC_{mass}/GDP and DMC_{mass}/Income (indexed 1878 = 100) for the Japanese economy in the period 1878–2005. The two indicators followed different paths in the period 1878–1930: DMC_{mass}/Income illustrates a strong increase, reaching 112%, while DMC_{mass}/GDP demonstrates a smoothly increasing trend by 20%. Reflected by both indicators, a period of decoupling was initiated around 1930, which intensified during WWII, a devastating period for the Japanese economy. Strong coupling trends, according to both the standard and the proposed MI_{mass} indicators characterized the postwar period (1945–1951). In the period 1950–1974 the two indicators followed substantially different trajectories: DMC_{mass}/GDP with relative stability resulting in an increase of 20.2%, while DMC_{mass}/Income sheer coupling trends of 58% (Table 4). The unprecedented growth rates, reaching an increase by 2669% for $GDP_{per\ Capita}$ required substantial augmentation in the consumption of mass resources by 4355%, during 1878–2005. Starting with 1974, the recent economic history of Japan has been characterized by clear dematerialization, evidence of which is depicted in both MI_{mass} indicators (Fig. 5).

Table 4 Estimates in indicative periods for Japan's DMC_{mass}/GDP and DMC_{mass}/Income

Period	DMC_{mass}/GDP (%)	DMC_{mass}/Income (%)
1878–1945	−25.7	55.9
1950–1974	20.2	58
1975–2005	−56	−49.7
1878–2005	**−54.2**	**60.7**

Japan's Disaggregate MI_{mass} for 1878–2005

Figure 6a–c depicts DMC_{mass}/GDP and DMC_{mass}/Income ratios indexed (1878 = 100) for all individual categories of mass resources: ores, non-metallic minerals, non-energy biomass. Both MI_{mass} ratios evolve along similar paths for ores (Fig. 6a) and "*non-metallic minerals*" (Fig. 6b) for the period 1878–1945. In 1946–1974, the "$DMC_{ores}/Income$" and the "$DMC_{non\text{-}metallic\ min}/Income$" present a strong coupling trend, compared to the moderate coupling of "DMC_{ores}/GDP" and "$DMC_{non\text{-}metallic\ min}/GDP$" ratios. Remarkably, ores and non-metallic minerals increase their relative share of total resources in this period, (Fig. 6b). "Ores" and "non-metallic minerals" present a decoupling trend in 1975–2005, for both MI indicators. The "$DMC_{biomass}/GDP$" and "$DMC_{biomass}/Income$" ratios (Fig. 6c) evolve with substantial differences for 1878–1930: the former a declining trajectory and the latter a rather fluctuating stability with a smooth declining. After 1930, both ratios moved along similar evolutionary paths coupling until 1950; with decoupling from 1950 until 2005. Notably, "*(Non-energy) biomass*" shrinks its relative share with accelerating trends after the end of WWII (Fig. 7).

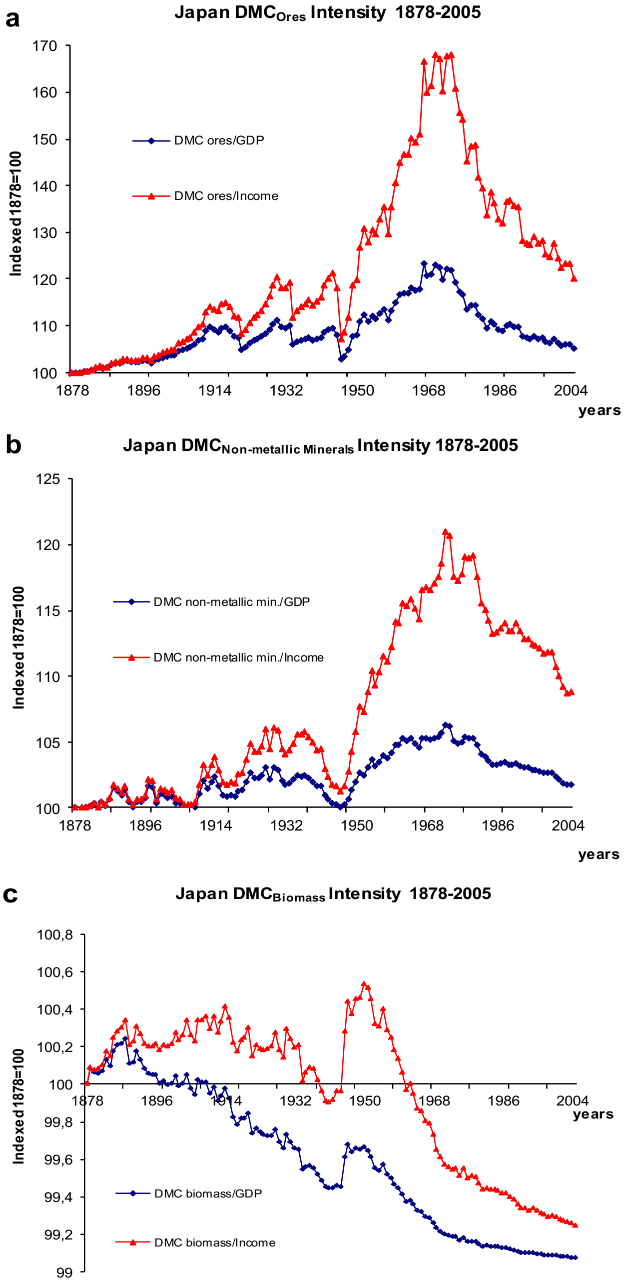

Fig. 6 **a** DMC_{Ores}/GDP and DMC_{Ores}/Income; **b** $DMC_{non\text{-}metallic\ min}$/GDP and $DMC_{non\text{-}metallic\ min}$/Income; **c** $DMC_{Biomass}$/GDP and $DMC_{Biomass}$/Income, for the period 1870–2005 (indexed as 1878 = 100)

Conclusions

As an indirect revival of an old yet historical "aphorism" in the literature of biophysical and ecological economics (Georgescu-Roegen 1977), it seems that matter does matter in the economic process. Mass resources are important inputs into the economic process and economic growth utilizes huge and still increasing amounts of material flows

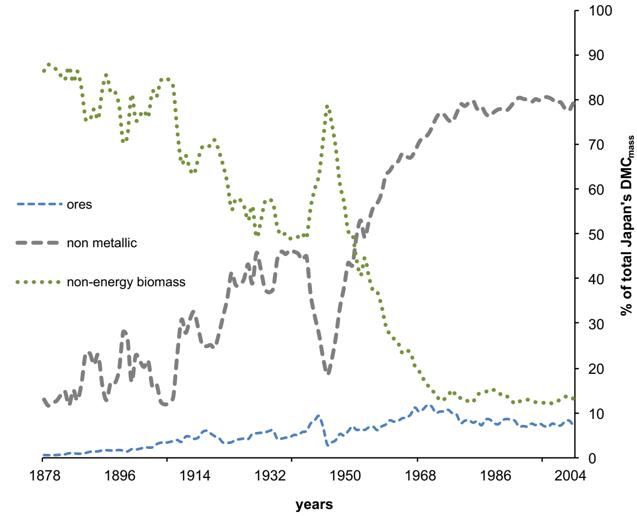

Fig. 7 Relative composition of the Japanese DMC_{mass} (%) during 1878–2005

(De Bryun 2002; Bringezu et al. 2004; Ekins 2008; Dittrich et al. 2012; Wiedmann et al. 2015). We evaluated the mass Material Intensity (MI_{mass}) of economic growth for the global economy and two post-industrial and high-technology countries. We compared standard MI_{mass} estimates, which follow the prevailing resource intensity framework, with estimates adopting the income index as the appropriate monetary variable for the outcome of the economy and hence for evaluating resource intensity. The differences are fundamental and have crucial implications for resource scarcity, economic science, and environmental policy. The prevailing MI_{mass} estimates feed on optimism over the prospects of green growth as the dependency of growth on material resources has been continuously decreasing over the last 100 years or so. On the contrary, once $GDP_{per\ capita}$ is adopted as the appropriate index for the outcome of the economy, it becomes apparent that the mass requirements of the global economy over the last 100 years are increasing. The drastically increasing $GDP_{per\ capita}$, a reflection of increasing welfare, requires enormous mass inputs. Between 1900 and 2002, the mass inputs consumed to produce one unit of income increased by 45.5%. Indeed, matter does matter, as mass inputs are increasing disproportionately to support a higher economic utility–welfare. This trend, combined with a 301.4% increase in global population, resulted in a 617% increase in the aggregate mass resource consumption to support global growth, signaling that the per capita consumption of mass resources increased by 78.7% over the last century (1900–2002). Overall, these findings demonstrate an increasing link between mass and growth at the global level. The increasing population, prior to consuming telecommunication, services, and financial "products," seeks to satisfy basic needs, such as housing, food, and transport, which are provided by goods whose production requires increasing mass flows, and hence are mass-intensive goods.

Indeed, matter matters for the global economy. Our study compares the trends at the global level with two economies which exhibit extremely high expectations of decoupling as they are among the leaders of the knowledge-based post-industrial world. The giant economies of USA and Japan increased their MI_{mass} until the 1970s, with the period after World War II indicating a rapid dependency of economic activities on mass resources. The USA and Japan initiated an actual decoupling around the middle of the 1970s, a trend that is still persistent in Japan and stabilized in the USA after 1990. This recent decoupling of growth from mass consumption may induce an optimism which however, requires a systematic analysis of the driving forces underlying the potential dematerialization effect.

Although the evaluation of the driving forces of decoupling is beyond the scope of the present study, some initial remarks will be attempted. Indeed, an increased efficiency in the use of resources, induced by the first oil crisis, was initiated in the 1970s. At the same time, the restructuring of the high-income economies towards "services" has promoted the decoupling of economic growth from mass resources. This decoupling force has been further boosted by the outsourcing of industrial production, in more recent years. However, the outsourcing of "*heavy*" production may result in a proportionate "coupling" in the developing countries. The increasing "coupling" at the global level may be perceived as an indication of a trend that strengthens the decoupling of the post-industrial world at the expense of intensified coupling in the developing countries. Inevitably, some skepticism over the driving forces of decoupling is induced by the empirical analysis which identifies contracting trends between the global economy and advanced national economies.

Accurate empirical estimates of the resource intensity are needed to fuel scientific analysis and the policy arena. The standard MI estimates, overwhelmed by the Resources/GDP prototype, could be seen as an initial attempt to elaborate the complex and multi-dimensional Resources-Economy link. We argue that although this first era of analysis led to important contributions, the core of the problem is still not being addressed. The dramatically increasing divergence between the "*resources required to produce one unit of GDP*" and the "*resources consumed per capita*" forms an indicative but persistent contradiction that cannot be explained within the standard decoupling literature. The present study attempts an improved evaluation of the R-E link by incorporating the actual outcome of the economy in the decoupling analysis. This evaluation, inspired by the essence of economics as the science investigating the optimal allocation of scarce production means to satisfy infinite human needs, can contribute to a new era of more accurate analysis and hence promote more effective and realistic resource consumption policies. Inevitably, before designing effective sustainability policies we need to clearly depict the biophysical actuality of resource use and this paper makes a contribution in this direction.

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