Science of the Total Environment 619–620 (2018) 338–351

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Unmasking decoupling: Redefining the Resource Intensity of the Economy

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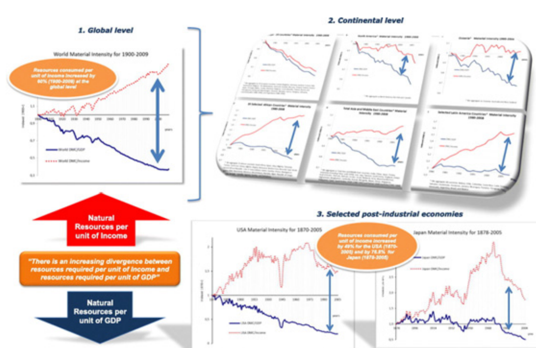
HIGHLIGHTS

- Resources consumed per unit of income increased by 60% (1900–2009) at the global level.
- Corresponding increases were 49% for the USA (1870–2005) and 76.8% for Japan (1878–2005).
- An increasing income required disproportionately increasing use of resources.
- After the 1970s, decoupling emerged in knowledge-based economies.
- This must be seen alongside strong coupling in the developing world.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 3 July 2017
Received in revised form 6 November 2017
Accepted 6 November 2017
Available online 29 November 2017

Editor: D. Barcelo

Keywords:
Decoupling
Dematerialization
Material intensity (MI)
Natural resource scarcity
Sustainable development
Economic welfare

ABSTRACT

Interest in investigating the complex link between resources and developments has revived recently following studies which support striking "dematerialized" growth over the last hundred years or so. This so-called decoupling effect is defined as the declining quantity of resources required for producing one unit of GDP. Decoupling studies adopt aggregate GDP as the measure of the outcome of the economy. However, this outcome is contributed by the total population which differs over time and between countries. A valid comparison should use a comparable, standardized indicator that adjusts for population size. GDP per capita, the income index, defines in monetary terms the ultimate outcome of the economy and is adopted by international organizations as the standard index for comparing economies. The income index approximates, in monetary terms, the welfare produced by the economic system and enjoyed by individuals. Recently developed alternative indexes of welfare lack broad data coverage and have limited empirical application as yet. For this reason and for ensuring direct comparison with the standard decoupling estimates, our study remains within the monetary context. The present paper re-evaluates the resources-economy link from the perspective of "the resources required for the production of one unit of GDP per capita (Income)" and hence evaluates the efficiency of turning resources into the actual outcome of the economic system. Our estimates suggest that the dependence of global economic growth on natural resources has increased by over 60% in the last 110 years (1900–2009), contrasting with the prevailing decoupling estimates which suggest a reduction by 63%. We find that the actual decoupling, which began in the mid-1970s in post-industrial economies, is counterbalanced by the intensified resource intensity of several developing economies. Accordingly, in the pursuit of sustainability, the dematerialization target

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https://doi.org/10.1016/j.scitotenv.2017.11.061

needs to be more clearly incorporated into environmental policies and pervade contemporary economic thinking.

1. Introduction

How an economy depends on resources, and the consequent constraints this places on its prospects of growth, attracted the interest of scholars at an early date (Solow, 1974, 1978; Georgescu-Roegen, 1971; Daly, 1973). Dematerialization potentials - the independence of growth from resources - define the actual limits to growth induced by the scarcity of natural resources (Meadows et al., 1972; Daly, 1997; Ayres, 2007; Turner, 2008; Ayres et al., 2013; Ayres and Voudouris, 2014). In this context, it is of paramount importance to account for the energy and mass requirements of the economic process. From the early attempt of Ayres and Kneese (1969) to measure material flows by the mass balance principle, to the recent Material Flow Accounting (MFA) method (Fischer-Kowalski, 1998; Fischer-Kowalski and Hüttler, 1999; Eurostat, 2001; Fischer-Kowalski, 2011; EEA, 2012), various techniques have been developed for monitoring and assessing resource use in global (Krausmann et al., 2009; UNEP, 2011; Dittrich et al., 2012) and national economies (Bringezu et al., 2003; OECD, 2004; Krausmann et al., 2011; Wang et al., 2016; Efthimiou et al., 2017). Today, MFA has developed into a framework of substantial maturity and methodological accuracy, offering a wide range of publicly accessible databases for empirical analysis that facilitate comparisons between methods and results (Fischer-Kowalski et al., 2011).

In MFA, the link between growth and natural resources is defined as the Material Intensity (MI) of the economy, and is estimated as the amount of resources required for the production of one unit of GDP. This key indicator, the ratio of Resources to GDP, is usually referred to as the "*Domestic Material Consumption/Gross Domestic Product*" [(DMC[1])/GDP] ratio. Supplementary indicators, such as DMC per capita, may provide some additional information which, however, does not characterize the core of the resources-economy link. The observation of declining trends in the DMC/GDP ratio is interpreted as signaling the so-called "decoupling effect", suggesting a gradual delinking of the economy from resources throughout the economic history of the last 100 years (Eurostat, 2001, 2002, 2009; Bringezu et al., 2004; Krausmann et al., 2009; UNEP, 2011; Krausmann et al., 2011; Gierlinger and Krausmann, 2011). This has important practical implications as contemporary studies of decoupling support the view that the independence of economic growth from natural resources is feasible under appropriate policies and institutions (Hatfield-Dodds et al., 2015; Schandl et al., 2016; Szigeti et al., 2017) - an optimism which, however, induces skepticism in other researchers (Lenzen et al., 2016; Ward et al., 2016; Bithas and Kalimeris, 2016; Bithas and Kalimeris, 2017; Alexander et al., 2018).

Declining trends in the DMC/GDP ratio contrast with the dramatically increasing trends in the per capita use of resources (DMC/population). This increase implies a fundamental dependence of the human system on resource use. Indicatively, per capita use of resources increased globally by 119.5% from 1900 to 2009, whereas the resources consumed in producing one unit of GDP (DMC/GDP) declined by 62.7% over the same period (Krausmann et al., 2009). In the USA, the former increased by 142.3% from 1870 to 2005 while the latter declined by 80% (Gierlinger and Krausmann, 2011). Despite this discrepancy, the recent literature shows a remarkable reliance on the trends in the resources required for one unit of GDP and supports a strong decoupling relationship in recent economic history.

In the present paper, we argue that the main reason for the contradictory evidence concerning the relationship between the human (socio-economic) and the natural systems supplied by the increasingly divergent trends in resources per capita and resources per unit of GDP is the defective evaluation of the Resources–Economy (R-E) link by the DMC/GDP ratio. Aggregate GDP reflects the scale of an economy - how big it is in monetary terms - but it says nothing about its actual outcome, that is, the satisfaction arising from the consumption of marketed goods. Yet the reason why the economic system produces goods and services is in order to satisfy human needs. Therefore, the number of human beings who share the aggregate outcome of the economy matters. The same aggregate GDP, distributed among different populations of individuals, may correspond to widely different economies with contrasting structures. India and France, for example, present very similar aggregate GDP (India 2,263,523 million US$, France 2,465,454 million US$[2]), yet no one would argue that India and France are similar economies, producing similar ultimate outcomes. The tremendous difference in population size (India 1,342,500,000 persons, France 64,942,000) makes comparison in terms of aggregate GDP meaningless as far as indicating the ultimate outcome of these economies goes. We are driven to consider instead the GDP per capita index, which is 1686 US$ for India and 37,964 US$ for France, in order to express the difference between the two economies. Population size is among the decisive driving forces of both production and consumption and determines the relative shares of the economic sectors (Brooks and Andrews, 1974; Samuelson, 1985). Remaining within the monetary context, the widely used indicator that approximates the outcome of the economy, while incorporating total population and its implications for the structure of the economic system, is GDP per capita, the income index (Kaldor, 1939; Hicks, 1939; Pigou, 1951; Samuelson, 1950; Sen, 1979). This has promoted the use of GDP per capita (Income) as the operational index for classifying economies into developed and developing ones by international organizations (Eurostat and OECD, 2012; OECD, 2013), reflecting the different level of economic welfare enjoyed by individuals in the two groups of countries. Notably, GDP and hence GDP per capita, have certain shortcomings in their ability to reflect economic welfare and even more in relation to depicting human well-being. Criticism of the use of GDP-based indexes has recently increased (van den Bergh, 2010; Daly, 2013; Costanza et al., 2014) and pioneering scientific attempts to develop alternative indexes in place of the flawed GDP have appeared in the literature. Green National Product (GNP), the Human Development Index (HDI), the Index of Sustainable Economic Welfare (ISEW) and the Genuine Progress Indicator (GPI) promise to overcome the limits of GDP-based indexes and provide a better measure of the actual outcome of the socio-economic system (Cobb and Daly, 1989; Cobb and Cobb, 1994; Stiglitz et al., 2009). However, these indexes are still in the development phase and the requisite empirical data are available for only a limited number of economies and for shorter periods than GDP-based indexes. (Lawn, 2003; Coyle, 2016) Taking into account the lack of data as well as our desire to focus on direct comparison with the standard dematerialization estimates, we confine our study to the monetary realm with due acknowledgment of its limitations, with ignorance of environmental externalities a particularly pertinent one.

The present study proposes the *materials required for the creation of one unit of income* (DMC/Income) ratio as an alternative indicator for

[1] Domestic Material Consumption (DMC) equals domestic extraction (DE) plus material imports, minus material exports: DMC = DE + Imports − Exports.

[2] GDP, Income and Population data source: http://data.worldbank.org/data-catalog/world-development-indicators. Retrieved in September 2017.

evaluating the R-E link. Since the concept of income encompasses in monetary terms the ultimate outcome of the economy, we assert that Income is the appropriate monetary measure for evaluating the Material Intensity (MI) of an economy and therefore the DMC/Income ratio is the indicator which best approximates the actual Material Intensity of growth. It goes without saying that the proposed indicator shares with the prevailing one all those shortcomings inherent in monetary-based indices.

Our proposed approach places the economic process within the framework of Coupled Human and Natural Systems (CHANS) (Liu et al., 2007, 2013; McConnell et al., 2011). Within CHANS, the economic process is envisaged as a process producing goods and services by and for all people. We estimate and compare the trends in Material Intensity (MI) as indicated by the proposed DMC/Income and standard DMC/GDP ratios for the global economy (1900–2009), the USA (1870–2005) and Japan (1878–2005), three cases with long-run data that allow a historical analysis of the R-E link over a period of enormous economic growth and technological advance. Secondly, we evaluate the MI at the continental level for North America, Latin America (18 countries), Europe (29 countries), Oceania, Africa (35 countries), and Asia and the Middle East, for 1980–2008. We also examine a number of indicative national economies with data available for 1980–2010: Australia, China, India, Brazil and Mexico. The seven individual national economies included in our study accounted for 56.15% of the global economy in 2013 (The Conference Board Total Economy Database™, 2014).

Indices relating GDP per capita to aggregate environmental variables are not entirely new in the analysis of the link between the environment and the economy. The best example is offered by the Environmental Kuznets Curve (EKC), which focuses on the relationship between GDP per capita and environmental pressure (aggregate pollution, i.e. CO_2 measured in tons) (Panayotou, 1992). Also, several studies investigating the causal relationship between energy consumption and economic growth use GDP per capita as a measure of economic growth (Soytas and Sari, 2003, 2006; Lee, 2006; Huang et al., 2008; Kalimeris et al., 2014). Recent studies have evaluated the energy requirements (Brown et al., 2011; Bithas and Kalimeris, 2013; Bithas and Kalimeris, 2016; Capellán-Pérez et al., 2014) and CO2 emissions (Salahuddin and Gow, 2014) involved in producing one unit of GDP per capita.

2. Redefining the material intensity of growth

The reasoning behind the adoption of the GDP per capita (Income) ratio as the appropriate monetary level for evaluating the MI of growth can be summarized in three arguments and by a simple numerical example.

2.1. A simple numerical illustration

The essential contribution of the proposed index of DMC/Income to the evaluation of the MI can be laid out by means of a simple numerical example. Three economies with different characteristics are to be compared: Economies A, B and C present the same GDP and DMC; Economy B has twice the population of C and Economy A has twice that of B (Table 1). According to the standard analysis of resource intensity, A, B and C all have the same DMC/GDP, hence equal MI, suggesting exactly the same dependence on resources. However, it is evident that A, B and C represent substantially different economies as the same GDP is being distributed within very different populations; the produced goods must satisfy the needs of substantially different numbers of individuals. Inevitably, Economies A, B and C will have different breakdowns into sectors, with A probably being the most intensively oriented towards basic goods such as food and housing, whose production necessitates substantial input of resources. Different economic structures result in different resource requirements. This fact cannot be reflected in the DMC/GDP estimates. In contrast, the DMC/Income ratio, which is highest for A, indicates that it is the most heavily dependent on natural resources, with the higher percentage of basic goods in Economy A being one of the main causes. In this respect, Economy C, having the highest Income, represents a more service-oriented and knowledge-based economy with a relatively less intensive material requirement per unit of actual output.

Table 1
Example: economies with different population sizes and similar aggregate DMC and GDP.

Variables	Economy A	Economy B	Economy C
GDP	10,000	10,000	10,000
DMC	20,000	20,000	20,000
Population	2000	1000	500
Income	5	10	20
DMC/GDP	2	2	2
DMC/Income	4000	2000	1000
DMC/Population	10	20	40

2.2. Evaluating the MI of the ultimate outcome of the economy

The amount of resources required for the creation of one unit of income measures the efficiency of using resources in the economic process by comparing the actual physical inputs (material flows) with the actual output of the economic process. The economic system produces goods to satisfy human needs and thus creates economic welfare. The enjoyment of economic welfare is an individual phenomenon and economies of the same scale (equal GDP) provide substantially different outcomes, if different populations are the consumers of this same aggregate GDP. This is reflected by the GDP per capita index which has been adopted as the standard index for the actual outcome of the economy. GDP per capita indicates, within the monetary context, the value of the economic welfare enjoyed by one human being, the value of goods consumed by one citizen. This "income" available to each individual citizen is an analytical abstraction which is necessary and broadly accepted for attempting basic assessments. The concept of income lies at the foundation of contemporary economics, established through seminal contributions (Kaldor, 1939; Hicks, 1939; Pigou, 1951; Samuelson, 1950; Sen, 1979).

2.3. The implications of population size for the structure of the economy

A causal relationship exists between population size and the structure of the economic system. Population size is among the driving forces of production and determines the relative shares of the economic sectors (Brooks and Andrews, 1974; 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 implications of population size on the production of "basic goods". A larger population results, ceteris paribus, in a relatively larger production of basic goods (dwellings, transportation, food, infrastructure, and so on) which require substantial material inputs, and thus implies a relatively stronger correlation between production and resource inputs. The implications of population size for the structure of the economic system are approximated by GDP per capita, whereas they are completely ignored by aggregate GDP.

2.4. Human needs define the biophysical properties of goods

Considered as an integral part of the Coupled Human and Natural Systems (CHANS), the economic process is conditioned by biophysical laws. Human beings are the *causa efficiens*, the reason, behind the economic process and their needs determine the properties that goods should possess in the real world. Goods have specific biophysical properties which are essential so as to satisfy the human needs (Schaffartzik et al., 2016). The actual MI of the economy is the outcome of the biophysical properties of goods. Indicatively, human needs determine the actual physical size that goods should have and sets thresholds for the potential to "shrink" that size: a matchbox sized car or an apartment of $2m^2$ would never be functional for human beings. The evaluation of the MI at the level of aggregate GDP absolutely obscures the implications and limits imposed by the actual physical properties of goods. GDP is the aggregate amalgam of the monetary value of numerous goods, whose physical properties are inevitably diluted at the highest level of monetary aggregation. We suggest that the implications of the physical properties of production on the MI can be better approximated by down-scaling the monetary value of GDP to the level of GDP per capita. This reflects a set of goods in some sense definable in physical terms. GDP per capita indicates the monetary value of the set of goods consumed by the "average" citizen. The MI of GDP per capita thus estimates the material requirements for a bundle of goods whose composition better reflects the actual structure of production than GDP does. GDP per capita offers a better mirror, in monetary terms, of the goods actually produced in an economy; as GDP per capita increases, the structure of the economy orients increasingly towards service goods. The implications for the material requirements of the actual production can be better traced if estimated at a monetary level whose biophysical properties correspond to the biophysical properties of actual goods produced. GDP per capita denotes a monetary value in relation to human beings who are the final reason behind the production process and who endow goods with certain physical characteristics. Thus GDP per capita brings the cause of the economic process - human beings - into the framework of MI evaluation.

3. The Decoupling Index: estimating the elasticity of GDP and income to DMC

In the literature on resource intensity, the link between resources and the economy has also been approached by means of a supplementary index, "the elasticity of resources use to the outcome of the economy" (Tapio, 2005), known as the Decoupling Index (DI) (UNEP, 2011). For direct comparison with the findings of the prevailing decoupling analysis, we evaluate the elasticity of both GDP and Income to DMC. In order to smooth out short-term fluctuations of the economic cycles we use, instead of the proposed one-year period (UNEP, 2011), a time period of one decade[3] (for the World, the USA, and Japan) or six years (for Australia, China, India, Mexico, and Brazil), by calculating moving averages (Bithas and Kalimeris, 2013).

First, we estimate the DI for the standard DMC/GDP ratio:

$$\frac{(DMC_t - DMC_{t-1})/DMC_{t-1}}{(GDP_t - GDP_{t-1})/GDP_{t-1}} = \frac{\Delta(DMC)}{\Delta(GDP)} \tag{1}$$

where t is an averaged time period of one decade (or six years, as appropriate). Hence, $t-1$ represents the change from the average of one decade (or six-year period) to the next.

Secondly, we estimate the DI for DMC/Income, using the same formula (Eq. (1)) but with GDP replaced by GDP/capita.

The DI is interpreted as follows (UNEP, 2011):

- DI > 1: coupling between the two variables.
- 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.

Variations of ±0.2 (20%) around the turning point (that is, DI values between 0.8 and 1.2) are considered to constitute the weak coupling zone in various recent studies (Tapio, 2005; Zhang et al., 2015; Chen et al., 2014). In the context of the present study, we adopt the interval proposed by Tapio (2005) and the above classifications of decoupling into relative and absolute proposed by UNEP (2011).

We carry out estimation of the DI at the global level, for six continents (North America, Europe, Oceania, Latin America, Asia and the Middle East, and Africa), and for the USA, Japan, Australia, China, India, Brazil and Mexico, separately.

4. Data sources

4.1. Data on DMC

Global material consumption (denoted by DMC_{World} from here onwards) consists of fossil energy carriers (the aggregation of oil, coal and natural gas), biomass, ores-industrial minerals, and construction minerals for 1900–2009. These data are drawn from Krausmann et al. (2009).

DMC for the USA (1870–2005) and Japan (1878–2005) is estimated as the aggregate of domestically consumed fossil energy carriers (the aggregation of oil, coal and peat, and natural gas), biomass, ores and non-metallic (construction) minerals. Data for the USA are drawn from Gierlinger and Krausmann (2011) and for Japan from Krausmann et al. (2011). All DMC data for the world, the USA and Japan are available online at: http://www.uni-klu.ac.at/socec/inhalt/1088.htm.

DMC data for the aggregated continental estimates (1980–2008), as well as for Australia, India, China, Brazil and Mexico (1980–2010), are drawn from an online portal for material flow data (http://www.materialflows.net/home/) set up by Vienna University of Economics and Business (WU Vienna) and the Sustainable Europe Research Institute (SERI), in cooperation with the Institute for Energy and Environmental Research (IFEU) and the Wuppertal Institute (WI) (WU, 2014).

All DMC data is measured in thousands of metric tons per year (1000 t/yr)[4] and estimated following the established procedures of the Material Flow Accounting (MFA) framework.

4.2. Data on GDP, population and income

GDP and Income (GDP/capita) are expressed in millions of 1990 International Geary-Khamis (G-K) US dollars[5] per year (million 1990US$/yr). Population is expressed in millions of persons. Updated data on GDP and population are drawn from Maddison (2008), and especially from Bolt and van Zanden (2014) and the Maddison project (version 2013: http://www.ggdc.net/maddison/maddison-project/home.htm).

5. Analysis and results

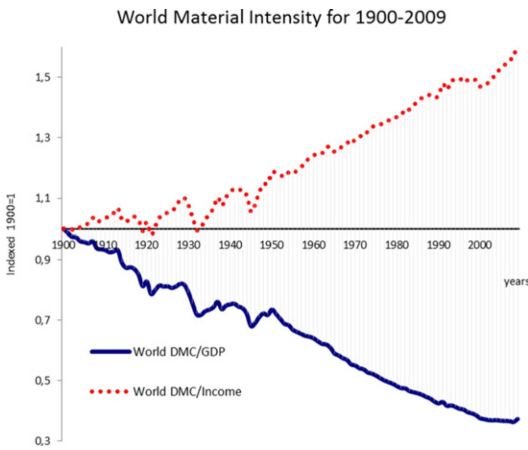
5.1. World MI for 1900–2009

Fig. 1 compares the trends in the DMC_{World}/GDP and DMC_{World}/Income ratios, indexed to 1900 as the base year (1900 = 1). DMC_{World}/GDP is clearly characterized by an overall decoupling trend throughout the period 1900–2009. This downward trend is partially interrupted in the period 1921–1950 by intervals of relative fluctuation, in particular during the Great Depression and early World War II (1921–1941) and the post-WWII period (1945–1950). The year 1950 is a milestone that marks the beginning of a steady long-term decrease in MI, lasting until 2000. Finally, relative stability appears in 2001–2009. Overall, the

[3] The decade period varies according to data availability. In some periods, within a case study, we use a different moving average period (i.e. six years for the period 2000–2005, in the cases of the USA and Japan).

[4] One metric ton equals 1000 kg, equivalent to 2204.62 lb (Cleveland and Morris, 2009, p. 326).

[5] 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 PPPs in Geary-Khamis dollars is available at http://unstats.un.org/unsd/methods/icp/ipc7_htm.htm.



Period	DMC/GDP (%)	DMC/Income (%)
1900-1945	-31.9%	5.6%
1950-2000	-48.9%	23.8%
2000-2009	-0.6%	10.7%
1900-2009	-62.7%	62.7%

Fig. 1. World MI for 1900–2009: DMC/GDP and DMC/Income ratios, indexed (1900 = 1); the table presents percentage changes for indicative periods.

DMC_{World}/GDP ratio decreased by 31.9% during 1900–1945, by 48.9% from 1950 until 2000 and hardly changed (−0.6%) during 2000–2009 (Fig. 1). The elasticity of GDP to DMC (the Decoupling Index - DI) remains within the relative decoupling zone (0 < DI < 1) throughout the period examined (Fig. 2).

The DMC_{World}/Income ratio evolves in sharp contrast to DMC/GDP (Fig. 1). The first half of the 20th century is characterized by a fluctuating coupling trend. Once again, the year 1950 constitutes a milestone for MI, as it sees the start of a protracted period of increasing DMC_{World}/Income amounting to 23.8% (1950–2000). Remarkably, the most recent period 2000–2009 is characterized by an accelerating increase of 10.7%. These coupling trends are confirmed by the elasticity of Income to DMC (DI), which remains well within the strong coupling zone from the 1970s up to the end of the period under study (Fig. 2). Clearly, according to the DMC_{World}/Income ratio, the global economy is becoming materialized, with notably increasing trends in recent years. This has crucial implications concerning the dependence of the world's economic system on natural resources.

5.2. MI at the continental level, 1980–2008

Fig. 3 shows estimates of MI separately for each continent, comparing DMC/GDP and DMC/Income indicators (all indexed to 1980 = 1). Data availability permits analysis over 1980–2008, following developments in the efficiency of the use of resources induced by the oil crisis of the 1970s and the restructuring of developed economies towards

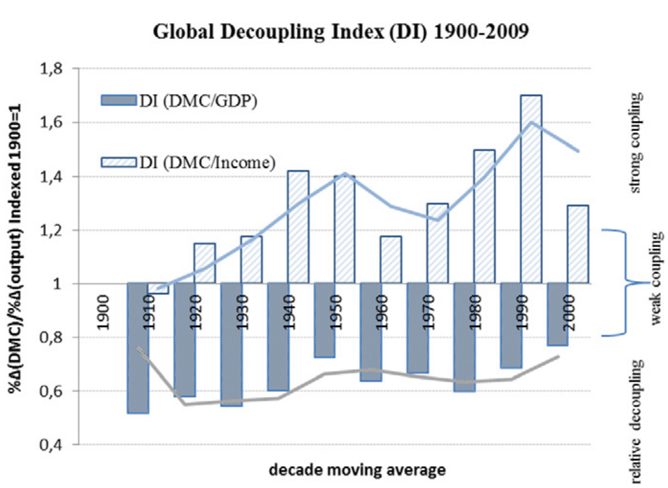


Fig. 2. World Decoupling Index (DI) for DMC/GDP and DMC/Income indicators, during 1900–2009 indexed (1900 = 1). The lines represent moving averages (decade time period).

service sectors. According to Table 2, Europe presents the most persistent dematerialization, reflected in both the DMC/GDP (−37.2%) and DMC/Income (−32.6%) ratios. In the case of North America, strong dematerialization according to the DMC/GDP indicator is apparent throughout the period examined (−43%), but only after the early 2000's for the DMC/Income indicator (−13.3% during 2000–2008). In Oceania, the DMC/GDP indicator suggests that after 1990 the dematerialization trend prevails (about −14% during 2000–2008) whereas DMC/Income shows a fluctuating stability with no signs of substantial decoupling (about 3% during 1980–2008). North America, Europe, and Oceania form the core of the so-called developed countries which have experienced the re-orientation of their economy towards knowledge-based production and the benefits from the technological progress.

Panels d–f of Fig. 3 present results for Africa, Asia-Middle East and Latin America, continents containing a high proportion of developing countries. Remarkably, increasing divergence is observed between the trends in DMC/GDP and DMC/Income. The African countries present a decoupling trend for DMC/GDP after 2000, amounting to −10.7% during 2000–2008. On the other hand, the DMC/Income ratio has increased drastically, by 66.1% during 1980–2008 and a further 7.3% during 2000–2008. The countries of Asia and the Middle East[6] show dematerialization up to −24% (1980–2008) according to the DMC/GDP ratio. However, this occurred mainly between 1980 and 2000, as the recent years 2000–2008 indicate only a marginal decrease of 2.3%. The DMC/Income ratio increases by 12.7% and 7.5% during 1980–2008 and 2000–2008, respectively. Latin America presents a relatively stable DMC/GDP ratio with two periods of decoupling, in 1983–1993 and 2003–2008, resulting in an overall change of −2.2% for 1980–2008, a period in which the DMC/Income index increased by 58.4%.

The estimates of the Decoupling Index (DI) confirm the MI trajectories (Fig. 4). Indeed, for the “developing” continents of Latin America (after 1995), Asia and the Middle East (1980–2008) and Africa (2000–2008), the elasticity of Income to DMC varies within the “weak” (0.8 < DI < 1.2) to “strong” (DI > 1.2) coupling zones. On the other hand, the elasticity of Income to DMC for Europe indicates strong decoupling (DI < 0.8), while in the cases of North America and Oceania it results in smooth (1990–2000) and strong coupling (1990–2000), respectively.

These continental estimates indicate two interrelated trends. Global materialization is largely the result of the performance of the developing continents which must be seen in the light of the dematerialization of the developed continents. This differentiation probably reflects the

[6] Asia and the Middle East include the highly developed economies of Japan, South Korea, Singapore and Israel. More details concerning the developed/developing countries classification can be retrieved from UN, 2014: http://www.un.org/en/development/desa/policy/wesp/wesp_current/2014wesp_country_classification.pdf.

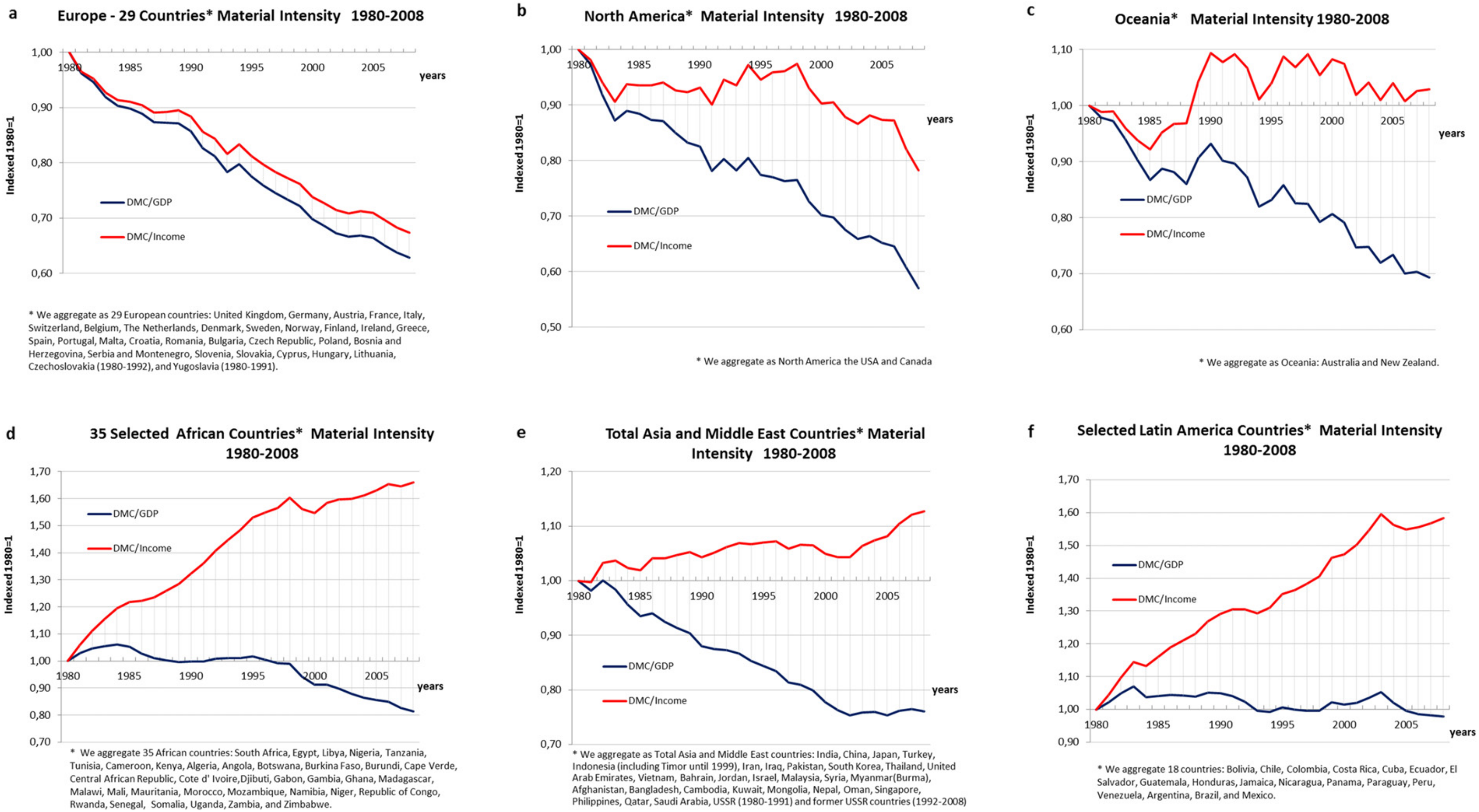


Fig. 3. Material Intensity on the continental scale during 1980–2008 for: a) Europe – 29 countries; b) North America; c) Oceania; d) Africa – 35 countries; e) Asia & the Middle East; f) Latin (South & Central) America – 18 countries (All Indexed 1980 = 1).

Table 2
Percentage change in Material Intensity for DMC/GDP and DMC/Income for a) Europe – 29; b) North America; c) Oceania; d) Africa — 35; e) Asia and the Middle East; f) Latin America.

a. Europe – 29			b. North America			c. Oceania		
Period	DMC/GDP (%)	DMC/Income (%)	Period	DMC/GDP (%)	DMC/Income (%)	Period	DMC/GDP (%)	DMC/Income (%)
1980–1990	−14.3%	−11.6%	1980–1990	−17.5%	−6.8%	1980–1990	−6.8%	9.4%
1990–2000	−18.5%	−16.5%	1990–2000	−15.0%	−3.1%	1990–2000	−13.5%	−1.0%
2000–2008	−10.1%	−8.8%	2000–2008	−18.8%	−13.3%	2000–2008	−14.1%	−5.0%
1980–2008	*−37.2%*	*−32.6%*	*1980–2008*	*−43.0%*	*−21.7%*	*1980–2008*	*−30.7%*	*2.9%*
d. Africa – 35			e. Asia & Mid-East			f. Latin America - 18		
Period	DMC/GDP (%)	DMC/Income (%)	Period	DMC/GDP (%)	DMC/Income (%)	Period	DMC/GDP (%)	DMC/Income (%)
1980–1990	−0.2%	32.2%	1980–1990	−11.9%	4.3%	1980–1990	4.9%	29.2%
1990–2000	−8.6%	17.1%	1990–2000	−11.7%	0.5%	1990–2000	−3.3%	14.0%
2000–2008	−10.7%	7.3%	2000–2008	−2.3%	7.5%	2000–2008	−3.6%	7.5%
1980–2008	*−18.5%*	*66.1%*	*1980–2008*	*−24.0%*	*12.7%*	*1980–2008*	*−2.2%*	*58.4%*

outsourcing of industrial production from the developed to developing world.

5.3. The MI of selected developed and developing countries

5.3.1. MI of the USA, 1870–2005

In the case of the USA, long-run data are available that permit an historical analysis of the MI trajectories. The DMC/GDP ratio shows steady dematerialization of the economy, resulting in an overall reduction by 80.1% from 1870 to 2005. In contrast, DMC/Income increased by 49.4% during the same period (Fig. 5). The DMC/Income ratio indicates a strong coupling trend for 1870–1973, except for a period of relative stability during 1915–1940 and a sharp but brief decoupling spell during WWII. After 1973, the DMC/Income ratio declines, suggesting a gradual dematerialization of the USA economy. The DI for the DMC/Income presents a trend which fluctuates mainly between the strong and weak coupling zones, except for just one period of strong decoupling occurring in the 1980s (Fig. 6).

5.3.2. MI of Japan, 1878–2005

Japan is the second national economy for which long-run data permit the analysis of a period of extremely high growth rates which increased income (GDP per capita) 27.7 times during 1878–2005. The path followed recently by the MI could be regarded as representative of a post-industrial economy which has evolved in the era of knowledge-based activities. During 1878–1945, DMC/Income presents a strong increase by 98.7%, whereas the standard DMC/GDP follows a smoothly decreasing trend by −5.3%. Strong coupling trends, apparent in both indicators, characterize the postwar period (1945–1951) when Japan was recovering from the devastating effects of WWII. During 1950–1974 the two indicators follow substantially different trajectories, with DMC/GDP initially indicating relative stability and then a smooth increase (11.1%), whereas DMC/Income shows steep coupling trends amounting to an increase of 46.1%. Starting in 1974, the recent economic history of Japan has been characterized by clear dematerialization, evidence for which is seen in both MI indicators (Fig. 7), as well as in the trends of the DI in the most recent years with available data (1980–2000, Fig. 8).

5.3.3. MI of Australia, 1980–2010

The DMC/GDP ratio for Australia is characterized by a decreasing trend during 1980–2010 (−40%), with smooth decoupling (−6%) in 1980–1990 and strong decoupling (−27%) in 2000–2010. On the other hand, the DMC/Income ratio shows coupling trends during 1980–1990 (9%), relative stability during 1990–2000 (−1.7%) and decoupling trends during 2000–2010 (−17.4%) (Fig. 9). The Income elasticity to DMC (DI) progresses from the relative decoupling seen in 1980–1985 into a strong coupling zone during 1990–2000 (DI > 1.2). However, subsequent DI trends bear out Australia's gradual dematerialization (from a relative towards a strong decoupling zone) during 2005–2010 (Fig. 10).

5.3.4. MI of China, 1980–2010

The DMC/GDP ratio for China shows relative stability for 1980–1993 and a downward trend thereafter, resulting in an overall decrease of 35.7% during 1980–2010. The DMC/Income ratio indicates a coupling period during 1985–1993 (≈11.4%) and a decoupling trend is observed after 2000 (−10.5%, 2000–2010) (Fig. 11). The elasticity of Income to DMC initially evolves within the weak coupling zone in 1985–1990 (0.8 ≤ DI ≤ 1.2), then presents a period of "strong coupling" during 1990–1995 (DI > 1.2), and ends up marginally in the weak coupling zone again during 2005–2010 (DI ≈ 0.75) (Fig. 12).

5.3.5. MI of India, 1980–2010

The DMC/GDP ratio for India shows an almost constant decoupling trend throughout the period examined (−52.1%) (Fig. 13). On the other hand, the DMC/Income indicator presents initially a smooth coupling trend (4.1%, 1980–1990) which turns into decoupling after 1990. The elasticity of Income to DMC initially provides evidence for strong coupling (DI ≈ 1.5 for 1980–1985), then enters the zone of weak coupling (DI > 0.8) during 1985–1995 and concludes in relative decoupling (DI < 0.8) in 2000–2010 (Fig. 14).

5.3.6. MI of Brazil, 1980–2010

Brazil is a typical example of a materialized developing economy in terms of both DMC/GDP (15.1% increase) and DMC/Income (85.4% increase) for 1980–2010. Nevertheless, the difference between the two ratios is noteworthy (Fig. 15). These findings are further confirmed by DI estimates, which show the elasticity of Income to DMC evolving within the strong coupling zone after 2000, whereas the elasticity of GDP to DMC moves from weak coupling in 1995–2005 to strong decoupling in 2005–2010 (Fig. 16).

5.3.7. MI of Mexico, 1980–2010

The DMC/GDP indicator for Mexico presents a fluctuating coupling period until 1988, when a fluctuating but generally decoupling path commenced, resulting in an aggregate change of −8.6% during 1980–2010 (Fig. 17). The DMC/income indicator shows a variable increasing trend throughout this period (50.4%). In line with the MI estimates, the elasticity of Income to DMC lies after 1995 within the strong coupling (DI > 1.2) zone, whereas the elasticity of GDP to DMC falls within the weak coupling zone, except for 2010 when DI < 0 (signaling strong decoupling) (Fig. 18).

6. Discussion

The present analysis attempts an improved evaluation of the contribution of resources to the economy during an epoch of enormous

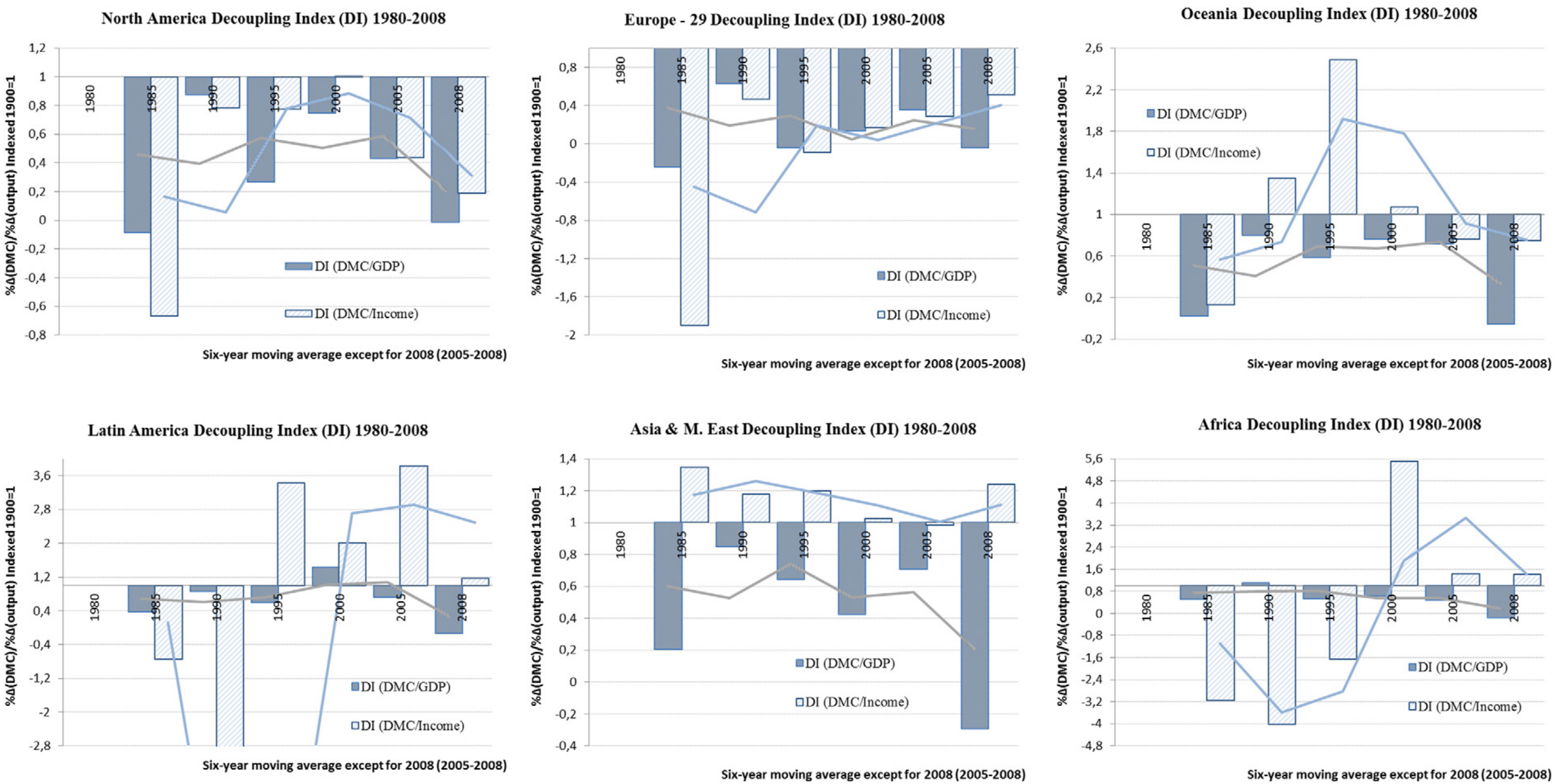
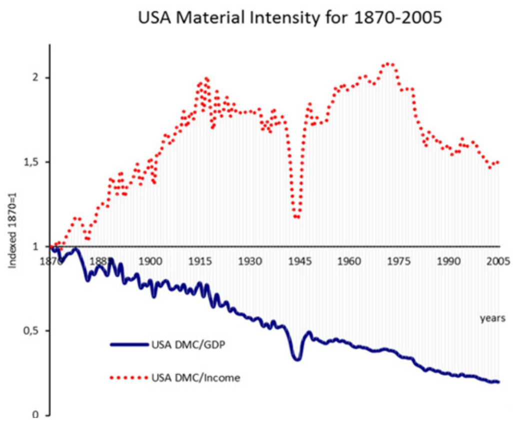


Fig. 4. The Decoupling Index (DI) of the MI trends estimated for the six continents examined. The lines represent the moving average per DI value (six-year periods, except for 2008 values (2005–2008)). In the case of Latin America, one outlying DI value (≈ − 16.5) has been excluded in order to improve the clarity of the figure.



Period	DMC/GDP (%)	DMC/Income (%)
1870-1945	-66.2%	19.8%
1945-1973	13.5%	73.5%
1973-2005	-48.2%	-28.1%
1870-2005	-80.1%	49.4%

Fig. 5. MI of the USA for 1870–2005: DMC/GDP and DMC/Income ratios (indexed 1870 = 1); the table presents percentage changes for indicative periods.

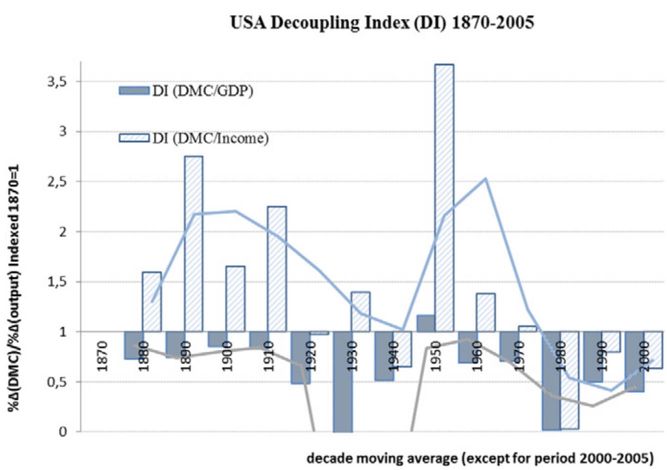


Fig. 6. The Decoupling Index (DI) of the USA for DMC/GDP and DMC/Income ratios during 1870–2005, indexed (1870 = 1). The lines represent the moving average per DI value (time period a decade) for each DI indicator. We have excluded an outlying DI value in 1990 (DI ≈ −3.6).

technological advances in the production process. The differences between the trajectories of the standard DMC/GDP and the proposed DMC/Income ratios bring into question the existence of the "decoupling effect" and the consequent optimism for sustainability prospects. The cases of the global, USA and Japanese economies attract especial interest since the availability of a long run of data permits an extended historical analysis of the Resources-Economy link throughout the 20th century, a period in which unprecedented growth rates resulted in a 5.8 times increase of global Income (GDP per capita) and 25.6 times increase of global GDP. According to the DMC /GDP ratio, the global economy shows a substantial decoupling of growth from material resources over the last 109 years (−62.7%). Similar trends prevail in the USA (−80%) and Japan (−49.6%). These decoupling trends are attributed

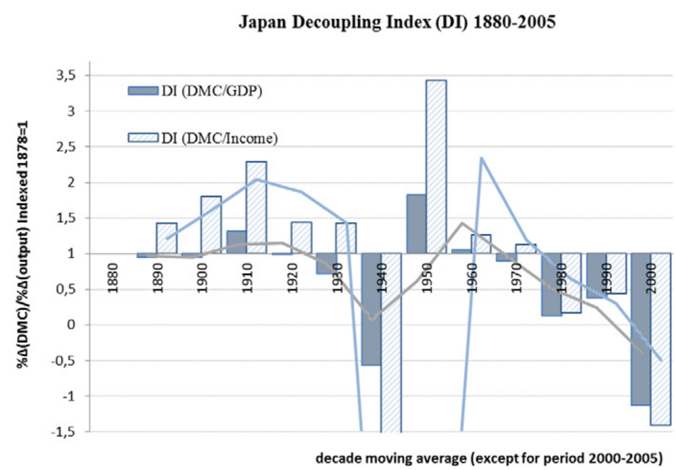
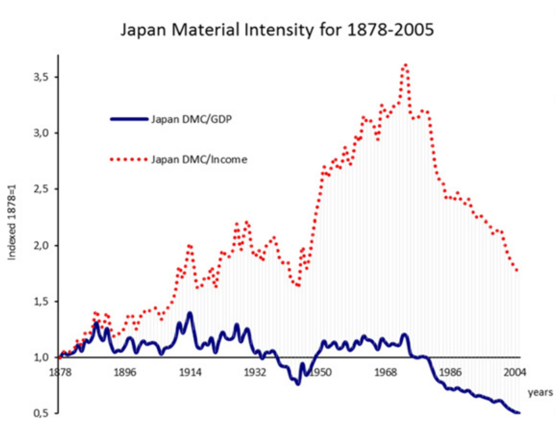
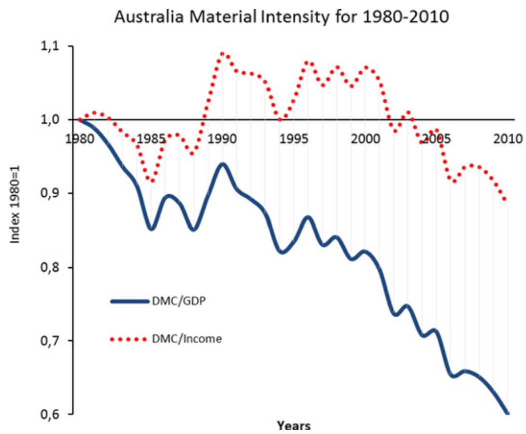


Fig. 8. Decoupling Index (DI) for Japan for the DMC/GDP and DMC/Income ratios during 1878–2005, indexed (1878 = 1). The lines represent the moving average per DI value (time period a decade) for each DI indicator. For greater clarity, we have excluded an outlying DI value in the 1940s (DI ≈ −16.2).



Period	DMC/GDP (%)	DMC/Income (%)
1878-1945	-5.3%	98.7%
1950-1974	11.1%	46.1%
1975-2005	-51.2%	-44.3%
1878-2005	-49.6%	76.8%

Fig. 7. MI of Japan for 1878–2005: DMC/GDP and DMC/Income ratios (indexed 1878 = 1); the table presents percentage changes for indicative periods.



Period	DMC/GDP (%)	DMC/Income (%)
1980-1990	-6.0%	9.0%
1990-2000	-12.6%	-1.7%
2000-2010	-26.9%	-17.4%
1980-2010	-39.9%	-11.6%

Fig. 9. Australia's MI for 1980–2010: DMC/GDP and DMC/Income ratios (indexed 1980 = 1); the table presents percentage changes for indicative periods.

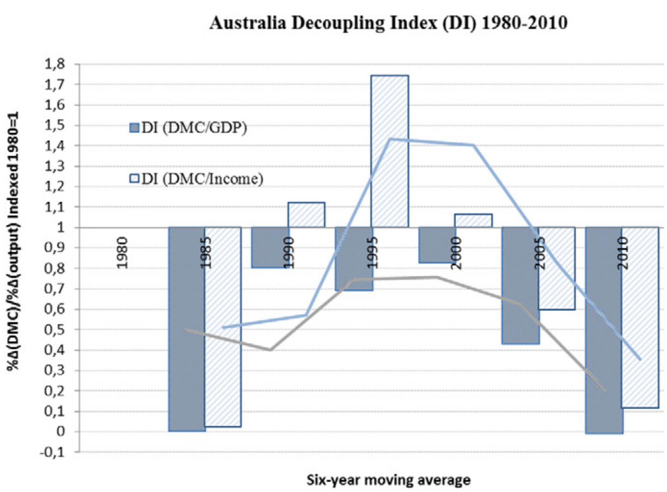


Fig. 10. Decoupling Index (DI) for Australia for DMC/GDP and DMC/Income ratios) during 1980–2010, indexed (1980 = 1). The lines represent the moving average per DI value for each DI indicator.

to the driving forces of technological advances, substitutions among materials and a service-oriented restructuring of the economy (Hatfield-Dodds et al., 2015). These factors have been augmented recently and induced a strong decoupling in the period of 1980–2010 throughout the so-called developed world. The economies of Europe (29 countries) and North America at the continental level, and the USA, Japan, and Australia at the national level, are all strongly driven by these forces, while outsourcing of industrial production has emerged as a new factor accelerating the decoupling trends of the advanced economies (Giljum and Eisenmenger, 2004; Munõz et al., 2009; Schandl and West, 2012). Remarkably, decoupling trends - according

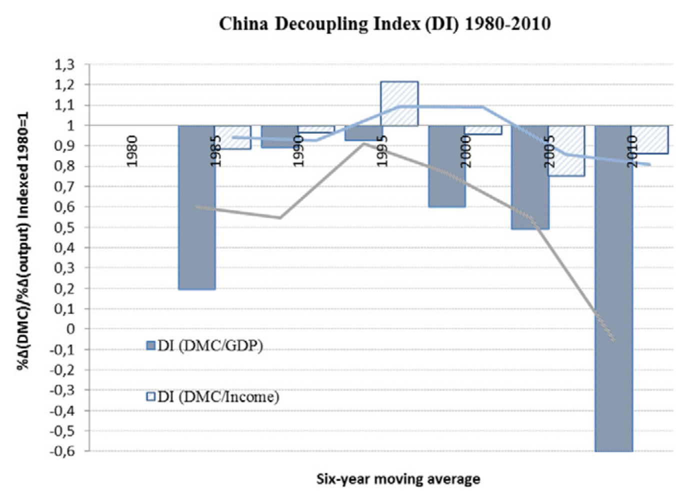
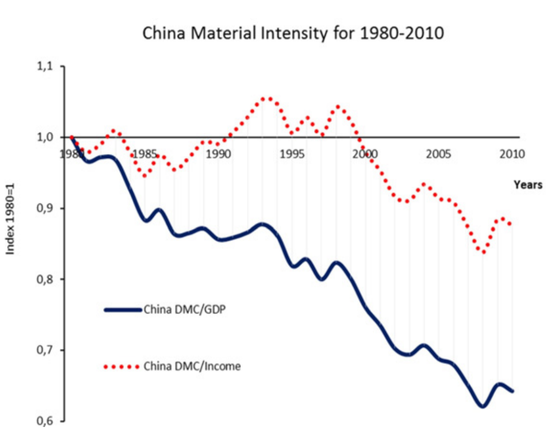
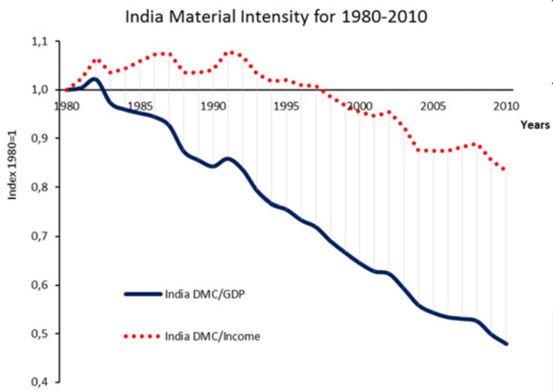


Fig. 12. China's Decoupling Index (DI) for DMC/GDP and DMC/Income ratios during 1980–2010, indexed (1980 = 1). The lines represent the moving average per DI value for each DI indicator.



period	DMC/GDP (%)	DMC/Income (%)
1980-1990	-14.4%	-0.9%
1990-2000	-11.2%	-1.2%
2000-2010	-15.5%	-10.5%
1980-2010	-35.7%	-10.5%

Fig. 11. China's MI for 1980–2010: DMC/GDP and DMC/Income ratios (indexed 1980 = 1); the table presents the percentage changes for indicative periods.



Period	DMC/GDP (%)	DMC/Income (%)
1980-1990	-15.7%	4.1%
1990-2000	-23.5%	-8.4%
2000-2010	-25.7%	-12.6%
1980-2010	-52.1%	-16.7%

Fig. 13. India's MI for 1980–2010: DMC/GDP and DMC/Income ratios (indexed 1980 = 1); the table presents the percentage changes for indicative periods.

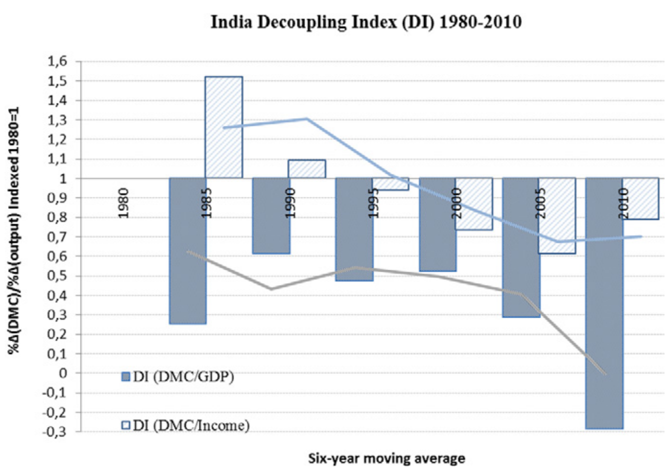


Fig. 14. India's Decoupling Index (DI) for DMC/GDP and DMC/Income ratios during 1980–2010, indexed (1980 = 1). The lines represent the moving average per DI value for each DI indicator.

to the DMC/GDP ratio - are also apparent for the majority of the developing economies, especially in the most recent years, with the exception of Brazil. For the period with available data (1980–2010), China and India follow a constant decoupling amounting to −35.7% and −52.1%, respectively; Mexico a smooth decrease of −8.6%; and the trends at the continental level indicate a reduction by −18.5% in Africa, −24% in Asia and the Middle East, and −2.2% in Latin America. These estimates strongly support a brighter vision of a global economic system that is achieving a substantial independence from resources. Natural resources are becoming less important for the economy of both the knowledge-based and the developing world.

Using the DMC/Income ratio results in substantially different MI trajectories for all the economies studied, apart from the continent of Europe (29 countries). Since 1950, the global economy has presented an upward trend in the quantity of resource inputs required in order to produce one unit of income, a trend which has recently been intensifying to reach an aggregate increase of 34% during 1950–2009. The USA

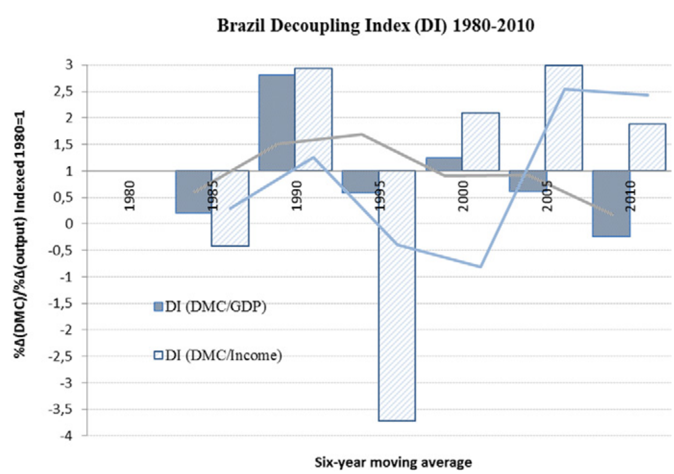
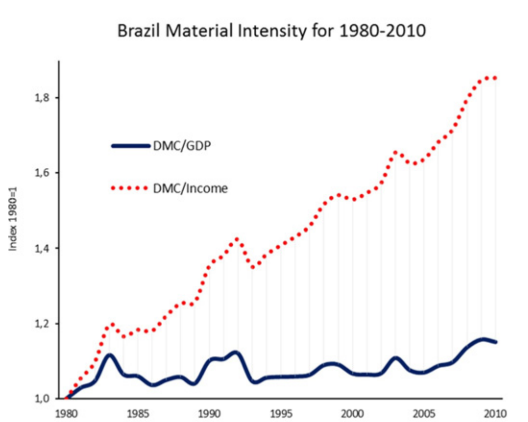
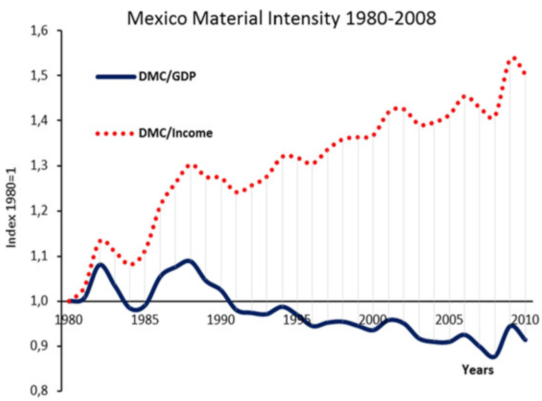


Fig. 16. Brazil's Decoupling Index (DI) for DMC/GDP and DMC/Income ratios during 1980–2010, indexed (1980 = 1). The lines represent the moving average per DI value for each DI indicator.



Period	DMC/GDP (%)	DMC/Income (%)
1980-1990	10.1%	35.3%
1990-2000	-3.1%	13.1%
2000-2010	7.9%	21.2%
1980-2010	15.1%	85.4%

Fig. 15. Brazil's MI for 1980–2010: DMC/GDP and DMC/Income ratios (indexed 1980 = 1); the table presents percentage changes for indicative periods.



period	DMC/GDP (%)	DMC/Income (%)
1980-1990	2.4%	27.3%
1990-2000	-8.7%	7.5%
2000-2010	-2.3%	9.9%
1980-2010	-8.6%	50.4%

Fig. 17. Mexico's MI for 1980–2010: DMC/GDP and DMC/Income ratios (indexed 1980 = 1); the table presents percentage changes for indicative periods.

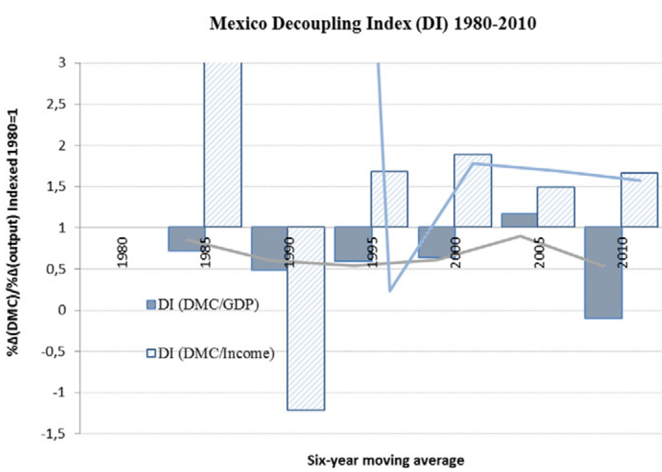
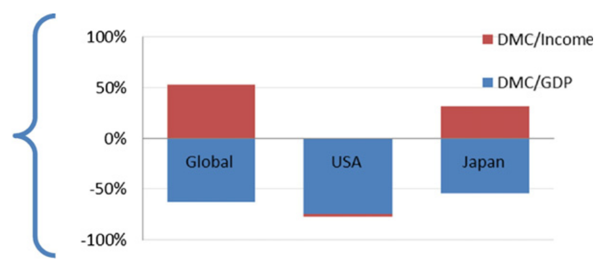


Fig. 18. Mexico's Decoupling Index (DI) for DMC/GDP and DMC/Income ratios during 1980–2010, indexed (1980 = 1). The lines represent the moving average per DI value for each DI indicator. For greater clarity, we have excluded an outlying DI value in 1985 (DI ≈ 41.5).

and Japan, two representative post-industrial economies which might be expected to exhibit strong dematerialization, built their recent resource efficiency upon a prolonged period of a strong coupling link between resources and growth. The USA MI increased up to 1970 and decreased sharply in 1970–1980, followed by smoothly decreasing trends thereafter; Japan's economy intensified its MI until 1974, with extremely strong coupling trends after WWII. A sharp dematerialization of the Japanese economy, confirmed by both MI indicators, began in the mid-1970s and lasted until the end of the period examined (2009). Is decoupling in the USA and Japan the result of increasing efficiency or should the cause also be sought in international trade, as these advanced economies export services and know-how while importing basic, material-intensive, goods? If the latter is the case, then recent dematerialization in Japan and the USA may well be based on the disproportionate materialization of certain developing economies (Bawa et al., 2010; Wiedmann et al., 2015). Indications in recent years of an exchange of the dematerialization of the developed economies for further materialization of the developing ones are supported by the DMC/Income estimates at both the national and the continental levels. Strong materialization trends clearly emerge in the developing economies of Mexico and Brazil, where economic growth is accompanied by a

a. Long run estimates (1900-2005)

	DMC/GDP	DMC/Income
Global	-63.3%	52.80%
USA	-75.2%	-2.1%
Japan	-54.4%	31.9%



b. Short run estimates (1980-2010)

	DMC/GDP	DMC/Income
Australia	-39.9%	-11.6%
China	-35.7%	-12.4%
India	-52.1%	-16.7%
Brazil	15.1%	85.4%
Mexico	-8.6%	50.4%

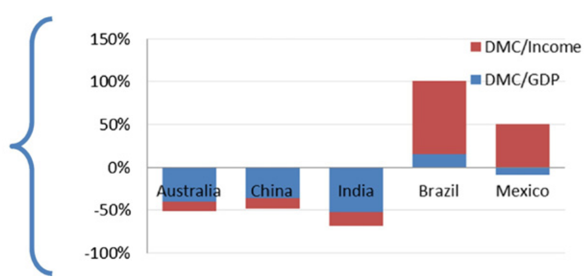


Fig. 19. Summarizing the differences. The percentage % changes between DMC/GDP and DMC/Income indices for a) Long-run estimates for the Global economy, the USA and Japan, for 1900–2005; and the b) Short-run estimates for Australia, China, India, Brazil and Mexico, for 1980–2010.

disproportionate increase in the use of resources. At the continental level, decoupling in Europe (−32.6%) and North America (−21.7%) must inevitably be seen through the prism of the strong coupling in Africa (66.1%), Asia and Middle East (12.7%) and Latin America (58.4%). Be that as it may, the driving forces which induce decoupling call for systematic research which lies beyond the scope of the present article.

To summarize our findings (see also Fig. 19), the trajectories of the DMC/Income ratio describe a global economy with increasing resource requirements driven mainly by the developing world. The estimates of the DMC/Income ratio suggest that there has been a shift in the Resources-Economy link of the advanced economies during recent years, essentially after 1980. This shift is much smoother than that estimated by the standard MI index and could hardly be perceived as indicating independence from natural resources without an in-depth evaluation of the factors responsible. The decoupling of the developed world should be examined in the context of changes in developing economies. Nevertheless, the periods around the mid-1970s and the beginning of 1980s represent a landmark concerning the link between resources and growth in advanced economies. The first oil crisis (1973) prompted serious skepticism regarding the dependency of growth on resources. It seems that certain economies enhanced their efficiency by investing in advanced technologies, prompting a more efficient use of resources, and by restructuring the economic sectors. The shift in MI trends achieved by the advanced economies in recent years is an interesting case and requires further scrutiny.

7. Conclusions

Growth still remains the most popular objective in economic policy and is perceived as the fundamental remedy for a great number of contemporary social problems, including poverty, exclusion, immigration, unemployment and national security. National administrations, political parties, central banks, professional unions and media are all in favor of growth (Ayres and Warr, 2004; Daly, 2013). The research community has provided substantial input: in 2015 alone, over 6500 papers contain the terms “growth” or “development” in their titles.[7] Concerns about the limits to growth induced by the scarcity of natural resources have been alleviated by recent empirical analysis supporting the so-called decoupling effect, signaling the dematerialization of growth. Declining trends in the “resources required for producing one unit of GDP” induce an optimistic view endorsing sustainability prospects through the independence from natural resources. We question the empirical estimates that appear to support this optimistic view. We argue that the actual outcome of the economy cannot be measured by the aggregate GDP as claimed by the prevailing literature which compares the physical size (resource inputs) with the scale of the economy. The outcome of the economy is the satisfaction - welfare - enjoyed by individuals through their use of goods exchangeable through markets. The number of individuals, the population size, embedded in an economy matters. Remaining within the monetary domain, a standardized monetary-based index, the income ratio, can alternatively be used to approximate the ultimate outcome of the economy, conditioning on the population size. The use of GDP instead of GDP per capita to report the performance of economies is prompted by the fact that population changes far more slowly than GDP does and consequently trends in GDP are used as a proxy for trends in GDP per capita. However, the level and trends of the actual GDP per capita, the income index, have important implications for the structure of the economy and its MI, as economies with the same GDP may be of fundamentally different natures due to serving the needs of different populations. The income index permits the evaluation of the ultimate output of an economic system – that is, the economic welfare enjoyed by individuals – in relation to the material inputs to the system.

[7] The number is based on hits returned by Google Scholar.

Our estimates of DMC/Income do not support a vision of a globally dematerialized economy. The decoupling effect has never been an actual phenomenon at the global level. The global economy increased its dependence on resources by 62.7% during 1900–2009 and by 23.8% during 1950–2009. Remarkably, changes in global MI have accelerated in the last few years, after 2000 or thereabouts. The empirical estimates of the DMC/Income ratio indicate that global economic growth is accompanied by a disproportionate increase in the use of resources. The increasing efficiency induced by technological advance has been offset by the disproportionally increasing production of heavy goods induced by a runaway increase in the global population demanding the satisfaction of its basic needs. Housing, transport, food, and so on are materially intensive goods requiring the input of large amounts of resources for their production. The same holds true for major developing economies. Nevertheless, the relatively recent shift in MI trends in the advanced economies, although much smaller than what is generally believed today, is an interesting development with important policy implications, with the caveat that part of this shift has been induced by outsourcing industrial production to the developing world. In order to draw operational policy lessons, scientific research should aim to shed light on those parameters that define the use of resources in the economic process and hence drove the shift in the MI of the post-industrial economies. However, before attempting an in-depth analysis of the driving forces behind any actual decoupling, we need to adopt the appropriate framework for evaluating the resources requirement of the economy. The present paper aims to contribute towards this objective. We suggest DMC/Income as an indicator that sheds light on the core of the Economy-Resources link and enriches resources analysis. This may permit the construction of an up-dated resources policy not wrongly influenced by a shallow optimism induced by the prevailing illusion of decoupling. Economic and environmental policies should clearly incorporate resource-efficient objectives and drive towards feasible sustainability objectives.

Acknowledgements

The authors would like to thank the handling Editor Prof. Dr. D. Barceló and two anonymous reviewers for their valuable comments and suggestions which substantially improved the early versions of the present study. We also deeply acknowledge the support of Prof. Dr. Jack Liu at Michigan State University and Prof. Dr. Clive Richardson at Panteion University, Greece, for the development of the analytical framework.

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