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Determining economic productivity under environmental and resource pressures: an empirical application

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Abstract

The current study is divided into two parts. Part I deals with the indices of resource and impact decoupling for 13 countries of the EU, for a period spanning from 1990 to 2011. Employing the major pressures, of GHG emissions, mineral resource extraction and land use, the different cases of relative/absolute and no decoupling are determined. Part II uses data envelopment analysis to determine the resource productivity index on the basis of the same sample of countries, over the same period of time. Resource productivity index attempts to quantify the simultaneous application and the interrelationships of decoupling indices. The index of the GDP is used as output, while the indices of material resources, land resources and GHG emissions are used as inputs. Then, the index of total factor productivity changes is decomposed into efficiency change and technical change, showing, respectively, whether the productivity gains come mainly from improvements in efficiency or are mainly the result of technological progress. Finally, the index of efficiency change is decomposed into pure efficiency and scale efficiency, showing, respectively, whether the major source of efficiency change comes mainly from improvements in pure technical efficiency or is mainly the result of an improvement in scale efficiency.

Keywords: Data envelopment analysis, Productivity, Decoupling index, Material resources, Land resources, GHG emissions, Economic growth, Elasticity

1 Background

Emissions of greenhouse gases, the extraction of mineral resources and land use are three major pressures with global impact. More specifically, greenhouse gas emissions (GHG) are of central importance to climate change. The extraction of mineral resources is the starting point of all abiotic material flows and determines the pressures which are related to the volume of work circle from the mining stage to manufacturing, final production, use, recycling and disposal. Land use, especially the change of land use, is significantly associated with the use of biomass for food and non-food purposes, the pressures on biodiversity and with the change and resilience of the ecosystem. In order to investigate the performance of socio-industrial metabolism that these parameters induce, their degree of decoupling from economic growth (decoupling indices (DI)) is studied.

Certainly there are other factors related to the performance of socio-industrial metabolism and can cause adverse environmental impacts, such as water abstraction which may change entire landscapes, eutrophication and acidification that change the quality of water and soils and affect biodiversity, the presence of persistent organic pollutants that create long-term health risks, etc.

In the effort to analyze the performance of socio-industrial metabolism and to further develop it in a sustainable manner, it is appropriate to distinguish between the dynamics and adjustment of its volume and structure on the one hand and the fine-tuning on the other hand (Bringezu 2006).

The first case concerns the megaton flows that may exceed certain natural capacity of the environment (e.g., the absorption of greenhouse gases) and social tolerance (e.g., changes in the landscape due to deforestation) (Angrick et al. 2014).

The second case distinguishes nanogram flows of dangerous compounds with potential toxic effects. The control of persistent organic pollutants (POPs) and other chemicals requires detailed analytical information, the institutional framework of which has already largely been in place. Nevertheless, international literature lags significantly in what has to do with monitoring and control tools of megaton consumption flows and the related that refer to preventive environmental policy (Angrick et al. 2014). As a tool for exercising preventive environmental policy, an input-oriented index could work (Bringezu et al. 2003, 2009).

This work which on a first level studies the decoupling indices from economic growth, on a second level attempts to contribute to the enrichment of literature on preventive policy tools, extracting the total factor productivity index of economic systems through an input-oriented model.

For the calculation of the total factor productivity index of economic systems, the estimates are made by the DEA method and are based on an input-oriented model. The index of GDP per capita is used as output, while the indices, in per capita terms, of material flows, land use and greenhouse gas emissions are used as inputs.

An essential point regarding the inputs and outputs is that they are not specified in the traditional sense of DEA. Although a production function requires the use of L and K, our intention is to see the direct effect of the three major environmental and resource pressures (emissions of greenhouse gases, the extraction of mineral resources and land use) with global impact on economic growth. The context of the current application demands them to be interpreted as the representative outputs and inputs relevant to the calculation of the efficiency index. An analogous macroeconomic context of DEA applications has been described in the literature (see among others Halkos and Paizanos 2016a, b, c; Halkos and Managi 2016; Halkos and Polemis 2016; Halkos 2013; Bampatsou et al. 2013; Bampatsou and Hadjiconstantinou 2009; Ramanathan 2006; Golany and Thore 1997).

The total factor productivity index is a measure of production efficiency and is defined as the ratio of total output to total input (Fischer et al. 2009; Kitcher et al. 2013). The idea of the total factor productivity index was originally suggested by Malmquist (1953), and its growth can be measured using the Malmquist index. The Malmquist index of total factor productivity growth was developed through a general production function framework by Caves et al. (1982). Malmquist's total factor productivity index can be used to measure the total factor productivity change (TFPCH) of decision-making units

(DMUs) between two data points, by calculating the ratio of the distances of each data point relative to a common technology.

Where there is a panel data availability, the TFPCH index can be decomposed into its components which are indicators of efficiency change (EFFCH) and technical change (TECHCH). This helps to determine whether the increase of productivity over multiple time periods is a result of an improvement in technical efficiency or due to a technological progress. On a second level, the EFFCH index can be decomposed into the index of pure efficiency change (PECH) and the index of scale efficiency (SECH). These indices indicate the main source of changes in the technical efficiency index.

The following sections are concerned with the methodology for determining the decoupling indices (DI) and the index of total factor productivity change (TFPCH) and its components. Then, empirical analysis results are presented, followed by discussion and policy implications. Finally, the main conclusions are extracted.

2 Data and methodology

In order to determine the decoupling indices of material flows, land use and greenhouse gas emissions from economic growth, we use a data set for 13[1] countries (out of 15 EU countries), for a period spanning from 1990 to 2011 (i.e., $T = 13; N = 22$) (Additional file 1).

The data are summarized in Fig. 1 which records over time and in per capita terms the development trends of GDP, greenhouse gas emissions, material flows and land use.

2.1 Determination of decoupling indices DI

The decoupling index (DI) refers to the ratio of the percentage change in consumption of a given resource (material flows, land use), or the percentage change in production of a given pollutant emission (GHG emissions), to the percentage change of economic growth within a certain time period (e.g., 1 year).

Suppose the percentage change of resources consumption between periods t and $t-1$ is given by $\Delta P_t = \frac{(P_t - P_{t-1})}{P_{t-1}}$, while the percentage change of economic growth is given by $\Delta Y_t = \frac{(Y_t - Y_{t-1})}{Y_{t-1}}$. In that case, the decoupling index in year t is as follows: $\mathrm{DI}_t = \frac{\Delta P_t}{\Delta Y_t}$.

During the period 1990–2011, we calculate the elasticity $\frac{\mathrm{d}(\log y)}{\mathrm{d}(\log x)}$ at the means of the independent variables and more specifically from the marginal effect $\frac{\mathrm{d}y}{\mathrm{d}x}$ by using the chain rule: $\frac{\mathrm{d}(\log y)}{\mathrm{d}(\log x_i)} = \frac{\mathrm{d}(\log y)}{\mathrm{d}x_i} * \frac{\mathrm{d}x_i}{\mathrm{d}(\log x_i)}$.

Because $\frac{\mathrm{d}(\log x_i)}{\mathrm{d}x_i} = \frac{1}{x_i}$, we have

$$\frac{\mathrm{d}(\log y)}{\mathrm{d}(\log x_i)} = \frac{\mathrm{d}(\log y)}{\mathrm{d}x_i} \times \frac{x_i}{1} = x_i \times \frac{\mathrm{d}(\log y)}{\mathrm{d}y} \times \frac{\mathrm{d}y}{\mathrm{d}x_i} = \frac{x_i}{y} \times \frac{\mathrm{d}y}{\mathrm{d}x_i}$$

where y is the prediction function; x_i is the ith independent variable in the regression.In the case of continued economic growth, the decoupling index (DI) takes the following values:

When **DI** > **1**, the increasing rate of resource consumption or pollutant emissions is in line or is higher than the rate of economic growth. In this case no decoupling occurs. Alternatively, as the economy grows, resource consumption and environmental degradation increase rapidly.

[1] Belgium and Luxembourg excluded from the study due to data unavailability regarding the land use indicator, and hence, we have based our analysis in the remaining 13 countries of EU-15.

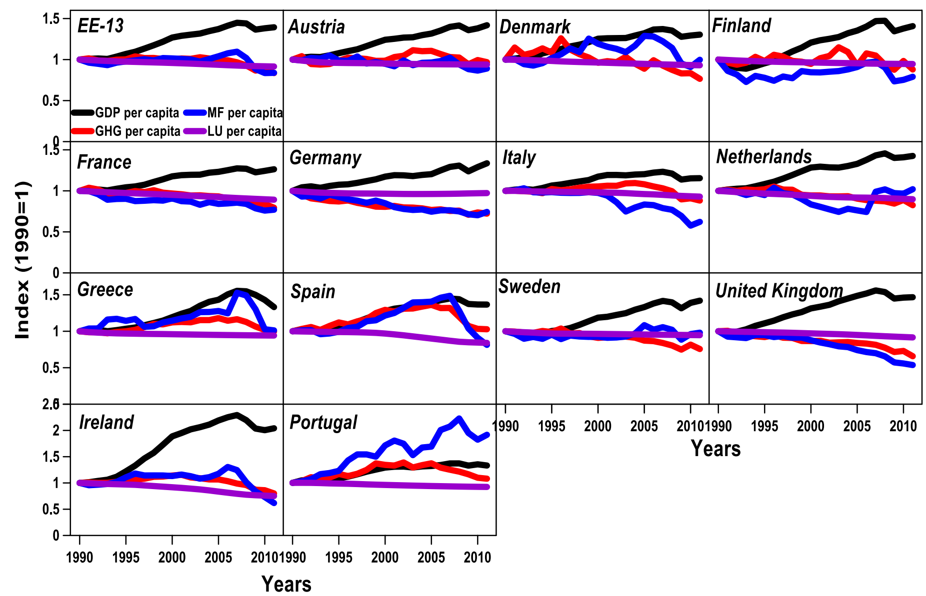

Fig. 1 Development trends of DMUs, *Source* EIA (2014), OECD (2014), SERI (2014)

When **DI** $= 1$, the condition is referred to as the turning point between absolute coupling and relative decoupling. In the stage of absolute coupling, a higher DI value implies greater dependence of economic growth in resources, lower resource efficiency and stronger environmental degradation.

When $\mathbf{0} < \mathbf{DI} < \mathbf{1}$, the growth rate in resource consumption or pollutant emissions is lower than the economic growth rate. If this occurs, then relative decoupling is taking place. When DI ranges from 0 to 1, lower DI implies greater resource efficiency and lower dependence of economic growth in resources.

When $\mathbf{DI} = \mathbf{0}$, the economy is growing, while resource consumption remains constant. In this case, the continuous growth of the economy is not accompanied by an increase of pollutant emissions.

When resources consumption or pollutant emissions decrease, while economic growth takes place, $\mathbf{DI} < \mathbf{0}$. In this case, the relationship between environment and economy can be characterized as absolutely decoupled (UNEP 2010, 2011; Bithas and Kalimeris 2013, 2016; WU Global Material Flows Database 2014).

2.2 The model for the determination of total factor productivity index

Following Fare et al. (1994), the input-oriented Malmquist productivity change index may be formulated as shown in (1):

$$M_I^{t+1}(y^{t+1}, x^{t+1}, y^t, x^t) = \left[\frac{D_I^t(y^{t+1}, x^{t+1})}{D_I^t(y^t, x^t)} \times \frac{D_I^{t+1}(y^{t+1}, x^{t+1})}{D_I^{t+1}(y^t, x^t)} \right]^{1/2} \quad (1)$$

where I indicates an input orientation, y denotes output, x denotes input, M is the productivity of the most recent production point relative to the earlier production point, and D denotes the input distance function.

The first ratio inside the brackets represents the Malmquist index for period t. It indicates the earlier production point (x^t, y^t), using period t technology. It measures productivity change from period t to period $t + 1$ using the technology level at period t as a benchmark. In this case, where the input Malmquist productivity index is based on the technology of period t, the result is:

$$M_I^t = \frac{D_I^t(y^{t+1}, x^{t+1})}{D_I^t(y^t, x^t)} \quad (2)$$

The second ratio inside the brackets represents the Malmquist index for period $t + 1$. It indicates the most recent production point (x^{t+1}, y^{t+1}) using period $t + 1$ technology. It measures the productivity change from period t to period $t + 1$ using the technology level at period $t + 1$ as a benchmark. In this case, where the input Malmquist productivity index is based on the technology of period $t + 1$, the result will be:

$$M_I^{t+1} = \frac{D_I^{t+1}(y^{t+1}, x^{t+1})}{D_I^{t+1}(y^t, x^t)} \quad (3)$$

The Malmquist productivity index can even be presented in an equivalent form as shown in (4):

$$M_I^{t+1}(y^{t+1}, x^{t+1}, y^t, x^t) = \frac{D_I^{t+1}(y^{t+1}, x^{t+1})}{D_I^t(y^t, x^t)} \left[\frac{D_I^t(y^{t+1}, x^{t+1})}{D_I^{t+1}(y^{t+1}, x^{t+1})} \times \frac{D_I^t(y^t, x^t)}{D_I^{t+1}(y^t, x^t)} \right]^{1/2} \quad (4)$$

or

$$M_I^{t+1}(y^{t+1}, x^{t+1}, y^t, x^t) = \underbrace{\frac{D_I^{t+1}(y^{t+1}, x^{t+1})}{D_I^t(y^t, x^t)}}_{\text{EFFC}} \left[\underbrace{\frac{D_I^t(y^{t+1}, x^{t+1})}{D_I^{t+1}(y^{t+1}, x^{t+1})} \times \frac{D_I^t(y^t, x^t)}{D_I^{t+1}(y^t, x^t)}}_{\text{TECHC}} \right]^{1/2} \quad (5)$$

In Eq. (5), the Malmquist total factor productivity index is the product of a change in efficiency (EFFCH) over the same period and a measure of technical progress (TECHCH) as measured by shifts in the frontier measured at period $t + 1$ and period t.

As formalized by Färe and Lovell (1978), the input-oriented efficiency measure of Farrell (1957) is the same as the inverse of Shephard's (1970) input distance function, which provides the theoretical basis of the current study for the calculation of the Malmquist production index. Therefore, values greater than one of the input-oriented version of the Malmquist index indicate an improvement.

More specifically, the values of the Malmquist index and its components can be greater, equal or smaller than 1. If the Malmquist productivity index between time periods t and $t + 1$ is greater than 1, then there is an improvement in productivity. If the Malmquist productivity index is equal to 1, then the productivity remains unchanged, and if Malmquist productivity index is smaller than 1, then the productivity declines.

The second component (TECHCH) measures the shift of the empirical production frontier between time period t and $t + 1$, which indicates the shift in production technology of a DMU.

If EFFCH > TECHCH, then the productivity gains are primarily the result of an improvement in efficiency, while if EFFCH < TECHCH, then the productivity gains are mainly the result of technological progress (Charnes et al. 1993).

Furthermore, the index of efficiency change (EFFCH) is decomposed into pure efficiency change (PECH) and scale efficiency change (SECH) and therefore follows relationship (6).

$$\text{EFFCH} = \text{PECH} \times \text{SECH} \tag{6}$$

If the SECH index is greater than 1, then the changes that have occurred in the inputs between the periods t and $t + 1$, improve the efficiency scale.

If the PECH index is greater than 1, then the improvements in resource management enhance efficiency.

If PECH > SECH, then the major source of efficiency change (either increase or decrease) comes mainly from improvements in pure technical efficiency, while if PECH < SECH, then the major source of efficiency change is mainly the result of an improvement in scale efficiency (Charnes et al. 1993).

3 Empirical results

3.1 Part I: decoupling indices, DI

The development trends and the decoupling indices of greenhouse gas emissions, material flows and land use from economic growth are depicted in Figs. 2, 3 and 4, respectiv ely.

The left-hand side vertical axis of Figs. 2, 3 and 4 represents the index of greenhouse gas emissions per capita, the index of material flows per capita, the index of land use per

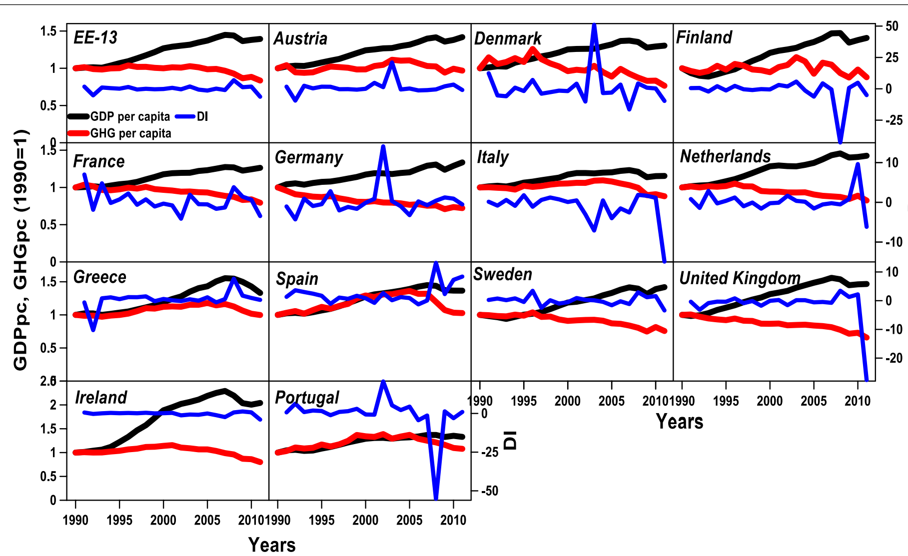

Fig. 2 Development trends and decoupling index in the case of GDP and GHG

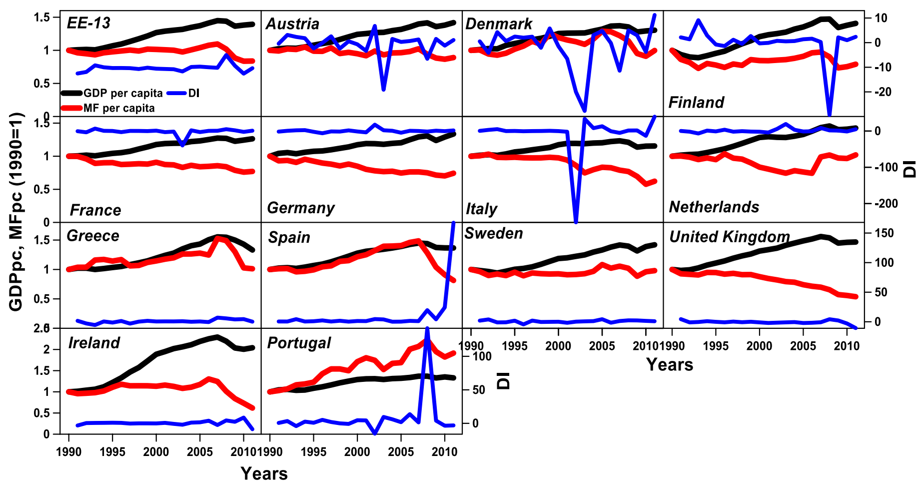

Fig. 3 Development trends and decoupling index in the case of GDP and MF

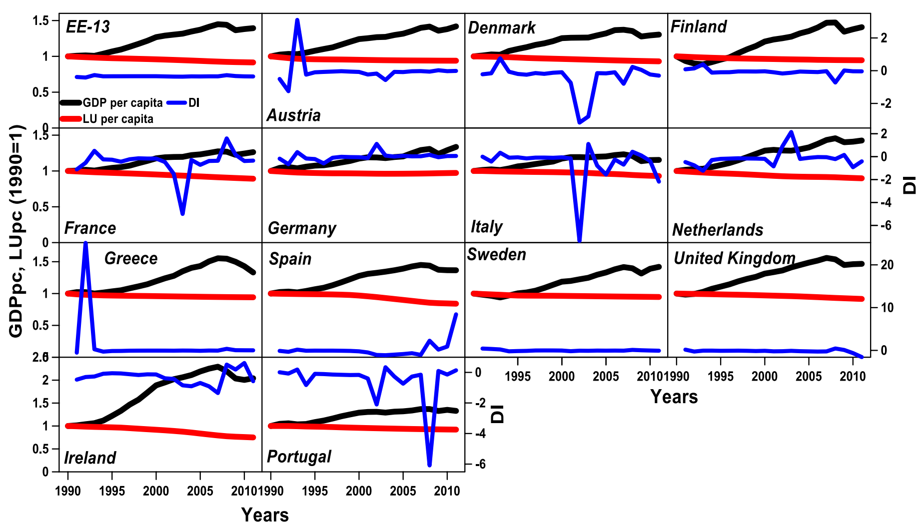

Fig. 4 Development trends and decoupling index in the case of GDP and LU

capita and the index of GDP per capita, while the right-hand side vertical axis represents for each case the decoupling indices in per capita terms.

In Table 1, countries are categorized by the degree of decoupling of economic growth from GHG emissions, material flows (MF) and land use (LU) during the period 1990–2011. The calculations are based on the determination of decoupling elasticity in the case of GHG, MF and LU.

Afterward is attempted a connection between country's performance in decoupling indices and its level of economic growth as depicted by Kuznets curve (UNEP 2011) in Fig. 5. In this way, the stage of growth at which one country is ranked, is determined according to its performance on decoupling index, in the case of material flows, land use and greenhouse gas emissions (Fig. 5).

Table 1 Decoupling elasticities

Country	Period	Decoupling elasticity$_{GHG}$	Decoupling elasticity$_{MF}$	Decoupling elasticity$_{LU}$
EU-13	1990–2011	$E_{GHG} = 0.1861187$	$E_{MF} = 0.3828582$	$E_{LU} = -4.938467$
AT	1990–2011	$E_{GHG} = 0.2939238$	$E_{MF} = -0.5953375$	$E_{LU} = -4.953718$
DK	1990–2011	$E_{GHG} = 0.0399113$	$E_{MF} = 0.2761444$	$E_{LU} = -3.825032$
FI	1990–2011	$E_{GHG} = -0.2397115$	$E_{MF} = 0.6710521$	$E_{LU} = -9.23818$
FR	1990–2011	$E_{GHG} = 0.5328471$	$E_{MF} = 0.4059508$	$E_{LU} = -4.063223$
DE	1990–2011	$E_{GHG} = -0.6367887$	$E_{MF} = -0.3449856$	$E_{LU} = 1.700767$
EL	1990–2011	$E_{GHG} = 0.3633368$	$E_{MF} = 0.3474602$	$E_{LU} = -6.34446$
IE	1990–2011	$E_{GHG} = 1.697216$	$E_{MF} = 0.031463$	$E_{LU} = -3.366314$
IT	1990–2011	$E_{GHG} = 0.8665963$	$E_{MF} = 0.1344858$	$E_{LU} = -3.820617$
NL	1990–2011	$E_{GHG} = -0.3733235$	$E_{MF} = 0.0468748$	$E_{LU} = -3.049892$
PT	1990–2011	$E_{GHG} = 0.2559368$	$E_{MF} = 0.109385$	$E_{LU} = -2.32407$
ES	1990–2011	$E_{GHG} = 0.7156735$	$E_{MF} = -0.0958734$	$E_{LU} = -1.604165$
SE	1990–2011	$E_{GHG} = -0.6977369$	$E_{MF} = 0.6773881$	$E_{LU} = -4.453933$
UK	1990–2011	$E_{GHG} = 0.8717215$	$E_{MF} = 1.308675$	$E_{LU} = -16.33951$

AT Austria, *DK* Denmark, *FI* Finland, *FR* France, *DE* Germany, *EL* Greece, *IE* Ireland, *IT* Italy, *NL* Netherlands, *PT* Portugal, *ES* Spain, *SE* Sweden, *UK* United Kingdom

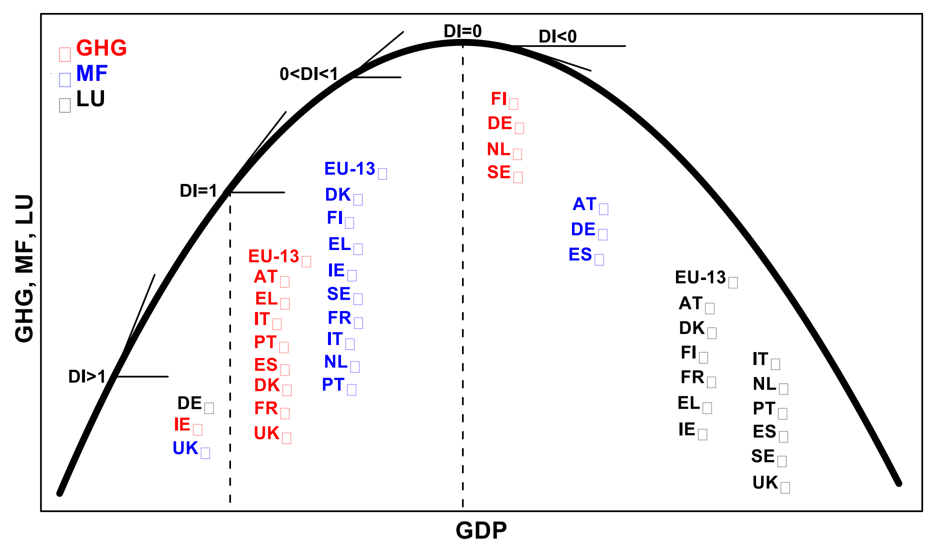

Fig. 5 Decoupling indices at different levels of economic growth

In Fig. 5, the decoupling indices of resources (material flows, land use) and environmental degradation at the different stages of economic growth are presented.

3.1.1 Analysis of the decoupling indices for the entire EU-13 and for each of the individual EU-13 countries

In the case of the entire EU-13, Denmark, France, Greece, Italy and Portugal, the decoupling elasticity indices of GHG and MF are positive, for a period spanning from 1990 to 2011. Relative decoupling (0 < DI < 1) is taking place, which means that the growth rate in MF consumption and GHG emissions is lower than the economic growth rate (Table 1).

These countries are recording negative elasticity, during the period 1990–2011, in the case of the decoupling index of LU from GDP. Absolute decoupling (DI < 0) is taking place, which means that the LU decreases, while the economy keeps growing (Table 1).

In the case of Austria and Spain, the decoupling elasticity index of GHG is positive for a period spanning from 1990 to 2011. Relative decoupling (0 < DI < 1) is taking place, which means that the growth rate in GHG emissions is lower than the economic growth rate (Table 1).

These countries are recording negative elasticity, during the period 1990–2011, in the case of the decoupling indices of MF and LU from GDP. Absolute decoupling (DI < 0) is taking place, which means that MF consumption and LU are decreasing, while the economy keeps growing (Table 1).

In the case of Finland, Netherlands and Sweden, the decoupling elasticity indices of GHG and LU are negative, for a period spanning from 1990 to 2011. Absolute decoupling (DI < 0) is taking place, which means that GHG emissions and LU are decreasing, while the economy keeps growing (Table 1).

These countries are recording positive elasticity, during the period 1990–2011, in the case of the decoupling index of MF from GDP. Relative decoupling (0 < DI < 1) is taking place, which means that the growth rate in MF consumption is lower than the economic growth rate (Table 1).

In the case of Germany, the decoupling elasticity indices of GHG and MF are negative, for a period spanning from 1990 to 2011. Absolute decoupling (DI < 0) is taking place, which means that GHG emissions and MF are decreasing, while the economy keeps growing (Table 1). Moreover, Germany shows elasticity greater than one during the period 1990–2011, in the case of the decoupling index of LU from GDP. No decoupling (DI > 1) is taking place, which means that the increasing rate of LU is higher than economic growth (Table 1).

In the case of Ireland, the decoupling elasticity index of GHG is greater than one for a period spanning from 1990 to 2011. No decoupling (DI > 1) is taking place, which means that the increasing rate of GHG is higher than economic growth (Table 1). In addition, Ireland shows positive elasticity during the period 1990–2011, in the case of the decoupling index of MF from GDP. Relative decoupling (0 < DI < 1) is taking place, which means that the growth rate in MF consumption is lower than the economic growth rate (Table 1). Finally, Ireland shows negative elasticity during the period 1990–2011, in the case of the decoupling index of LU from GDP. Absolute decoupling (DI < 0) is taking place, which means that LU is decreasing, while the economy keeps growing (Table 1).

In the case of the UK, the decoupling elasticity index of GHG is positive for a period spanning from 1990 to 2011. Relative decoupling (0 < DI < 1) is taking place, which means that the growth rate in GHG emissions is lower than the economic growth rate (Table 1). In addition, the decoupling elasticity index of MF is greater than one, for a period spanning from 1990 to 2011. No decoupling (DI > 1) is taking place, which means that the increasing rate of MF consumption is higher than economic growth (Table 1). Finally, the UK shows negative elasticity during the period 1990–2011, in the case of the decoupling index of LU from GDP. Absolute decoupling (DI < 0) is taking place, which means that LU is decreasing, while the economy keeps growing (Table 1).

3.2 Part II: TFPCH index and its components

Figure 6 summarizes and presents the empirical results on the determination of TFPCH index and its components (EFFCH index, TECHCH index, PECH index and SECH index).

In Fig. 6, countries are sorted in ascending order by the TFPCH index.

Subsequently, taking into account the relationships that have been recorded in the literature regarding the TFPCH indicators, an attempt is made to a further deepening and recording of the driving forces of total factor productivity index for DMUs under consideration (Table 2).

As already mentioned previously, the values of the TFPCH index and its components can be greater, equal or smaller than 1. If the TFPCH index is greater than one, then there is an improvement in productivity (productivity gains). Netherlands, Finland, Italy, Portugal, Spain, EU-13, Ireland, Austria, Sweden, UK, France and Denmark are countries

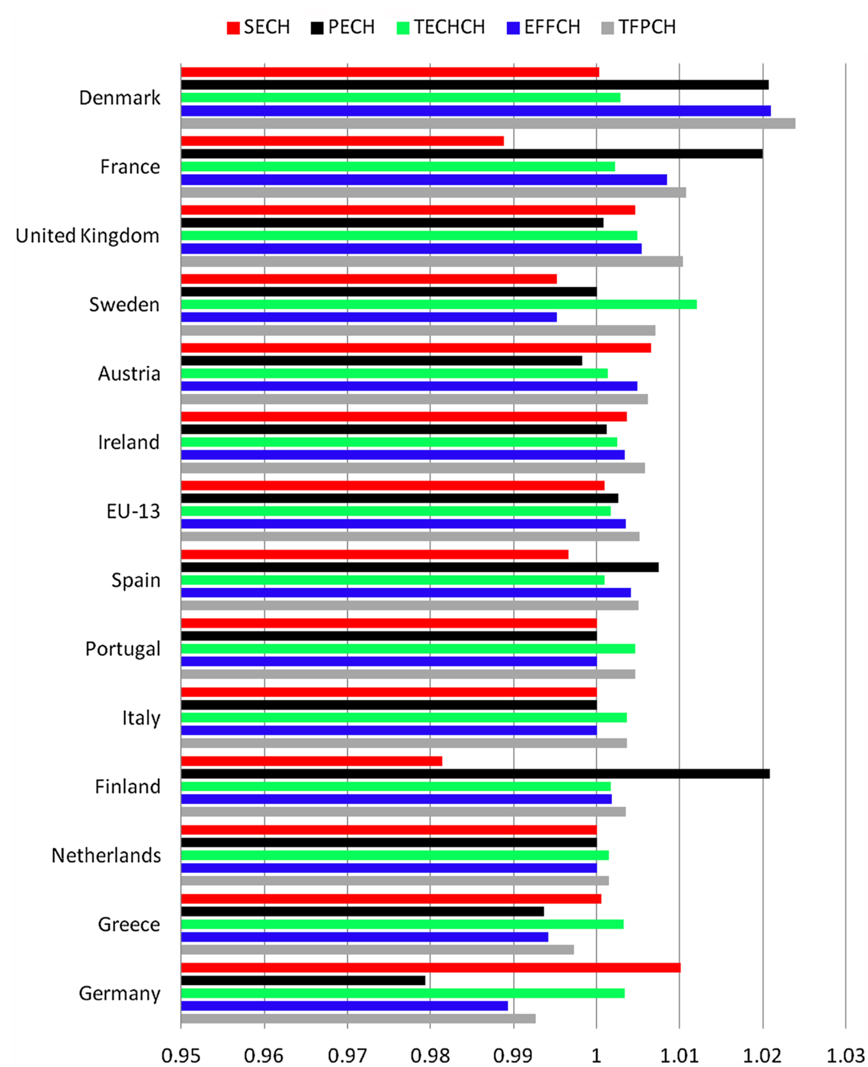

Fig. 6 Annual means of Malmquist index and its components. In this figure, countries are sorted in ascending order by the TFPCH index

Table 2 The driving forces of total factor productivity index of economic systems by country

T	DMU	Total factor productivity	The primary driving force of productivity	The primary driving force of efficiency change
1990–2011	Germany	Productivity loss	Technological progress	
1990–2011	Greece	Productivity loss	Technological progress	
1990–2011	Netherlands	Productivity gains	Technological progress	
1990–2011	Finland	Productivity gains	Improvement in efficiency	Improvement in pure technical efficiency
1990–2011	Italy	Productivity gains	Technological progress	
1990–2011	Portugal	Productivity gains	Technological progress	
1990–2011	Spain	Productivity gains	Improvement in efficiency	Improvement in pure technical efficiency
1990–2011	EU-13	Productivity gains	Improvement in efficiency	Improvement in pure technical efficiency
1990–2011	Ireland	Productivity gains	Improvement in efficiency	Improvement in scale efficiency
1990–2011	Austria	Productivity gains	Improvement in efficiency	Improvement in scale efficiency
1990–2011	Sweden	Productivity gains	Technological progress	
1990–2011	UK	Productivity gains	Improvement in efficiency	Improvement in scale efficiency
1990–2011	France	Productivity gains	Improvement in efficiency	Improvement in pure technical efficiency
1990–2011	Denmark	Productivity gains	Improvement in efficiency	Improvement in pure technical efficiency

that have productivity gains (Table 2). If the TFPCH index is equal to 1, then the productivity remains unchanged, and if it is smaller than 1, then the productivity declines (productivity loss). Germany and Greece are countries that have productivity loss (Table 2).

If EFFCH > TECHCH, then the productivity gains are primarily the result of an improvement in efficiency (Finland, Spain, EU-13, Ireland, Austria, UK, France, Denmark), while if EFFCH < TECHCH, then the productivity gains are mainly the result of technological progress (Germany, Greece, Netherlands, Italy, Portugal, Sweden) (Table 2).

If PECH > SECH, then the major source of efficiency change (either increase or decrease) comes mainly from improvements in pure technical efficiency (Finland, Spain, EU-13, Sweden, France, Denmark), while if PECH < SECH, then the major source of efficiency change is mainly the result of an improvement in scale efficiency (Germany, Greece, Ireland, Austria, UK) (Table 2).

4 Discussion and policy implications

The combination of knowledge derived from both the countries' classification on the Kuznets curve based on the decoupling indices (in the first part of the empirical analysis), as well as by the determination of the TFPCH index and its components (in the second part of the empirical analysis), may contribute to the optimal management of greenhouse gas emissions, mineral resource extraction and land use.

This study, through the decomposition of the TFPCH index into its EFFCH and TECHCH components, can be used as a policy-making tool for the EU-13 countries in order to improve their position, by achieving absolute decoupling of their economic growth from environmental and resource pressures.

From Fig. 5, we can see the degree of decoupling that each country succeeds at environmental and resource level. Regarding land use, there is absolute decoupling from economic growth to all the EU-13 countries with the exception of Germany where no decoupling occurs. In the case of greenhouse gas emissions and material flows, decoupling can be either absolute, which is the desired state, or relative. However, in many cases, there is no decoupling at all.

Our interest is primarily focused on the cases of the EU-13 countries, and we examine their decoupling status from the perspectives of economic growth. In cases where no decoupling and relative decoupling take place, we suggest some guiding policy lines aiming to improve the current decoupling status of the country under consideration. In this context, we identify the driving forces of the TFPCH index for each country (Table 2).

From Fig. 5 and Table 2, we can conclude with the following points:

1. In the cases of Germany and Greece, technological progress (TECHCH) is the primary driving force of the observed productivity loss.

Germany has achieved absolute decoupling in the case of GHG and MF indices. Therefore, the productivity loss may occur due to non-decoupling of land use from economic growth.

Greece has achieved relative decoupling in the case of GHG and MF indices. In Greece, the productivity loss may occur due to insufficiency of the technological progress to contribute significantly in reducing the environmental impact.

Productivity loss is interpreted somewhat differently for each of the two countries. In both of these cases, policy makers should be redirected toward policies to improve the technical efficiency index (EFFCH) in order to achieve the gradual transition from non-decoupling to relative and subsequently to absolute decoupling of land use in the case of Germany and to achieve absolute decoupling of greenhouse gas emissions and material flows in the case of Greece.

It should be noted that EFFCH index shows the deviation of the performance of the DMU under consideration from the best practice DMUs and is usually associated with managerial capabilities.

2. In the cases of Netherlands, Italy, Portugal and Sweden, technological progress (TECHCH) is the primary driving force of the observed productivity gain.

In these countries, policy makers should be redirected toward policies to further strengthen the technical change index (TECHCH).

It is worth noting that TECHCH index is associated with the changes in production technology, through innovations in resource-saving production methods.

Netherland and Sweden have already achieved absolute decoupling in the case of GHG and LU indices. Further strengthening of the production technology will gradually push the specific countries to the transition from relative to absolute decoupling in the case of material flows.

Italy and Portugal have already achieved absolute decoupling in the case of LU index. Further enhancement of the production technology will gradually push the specific countries to move from relative to absolute decoupling in the cases of greenhouse gas emissions and material flows.

3. In the cases of Finland, Spain, EU-13, France and Denmark, technical efficiency change (EFFCH) which derives from the improvement in pure technical efficiency (PECH) is the primary driving force of the observed productivity gain.

In these DMUs, policy makers should be redirected toward policies to further strengthen the indices of both technical efficiency (EFFCH) and pure technical efficiency (PECH).

It is worth noting that PECH index is associated with the changes in resource management and thus to the achievement of optimal allocation of resources in the production process. An improvement of the PECH index through a more efficient use of inputs and the investigation of the possibility of one DMU to optimize its internal organization can reduce inefficiency.

The entire EU-13, France and Denmark have already achieved absolute decoupling in the case of LU index. Further strengthening of both technical efficiency and pure technical efficiency will gradually push these DMUs to move from relative to absolute decoupling in the cases of greenhouse gas emissions and material flows.

Finland has already achieved absolute decoupling in the case of GHG and LU indices. Further enhancement of both technical efficiency and pure technical efficiency will gradually push the country to the transition from relative to absolute decoupling in the case of material flows.

Spain has already achieved absolute decoupling in the case of MF and LU indices. Further enhancement of both technical efficiency and pure technical efficiency will gradually push the country to the transition from relative to absolute decoupling in the case of greenhouse gas emissions.

4. In the cases of Ireland, Austria and the UK, technical efficiency change (EFFCH) which derives from the improvement in scale efficiency (SECH) is the primary driving force of the observed productivity gain.

In these countries, policy makers should be redirected toward policies to further strengthen the indices of both technical efficiency (EFFCH) and scale efficiency (SECH).

It is worth noting that SECH index illustrates the extent to which one DMU can improve its productivity by exploiting scale economies through the reduction of long-run average cost as production increases. Furthermore, it gives us useful information to choose the scale of production that will attain the expected production level. Inappropriate size of a DMU may sometimes be a cause of technical inefficiency.

Austria has already achieved absolute decoupling in the case of MF and LU indices. Further strengthening of both technical efficiency and scale efficiency will gradually push the country to the transition from relative to absolute decoupling in the case of greenhouse gas emissions.

Ireland has achieved absolute decoupling only in the case of LU index. Further enhancement of both technical efficiency and scale efficiency will gradually push the country to move from relative to absolute decoupling in the case of material flows, while in the case of greenhouse gas emissions the country will gradually move from non-decoupling to relative and then to absolute decoupling.

The UK has achieved absolute decoupling only in the case of LU index. Further enhancement of both technical efficiency and scale efficiency will gradually push the country to move from relative to absolute decoupling in the case of greenhouse gas emissions, while in the case of material flows the country will gradually move from non-decoupling to relative and then to absolute decoupling.

5 Conclusions

The aim of the present study is not only to determine the index of total factor productivity change (increase or decrease) but also to record its driving forces for the DMUs under consideration.

To determine the main sources of changes or alternatively the driving forces in the total factor productivity index, the TFPCH index can be broken down into the components of efficiency change (EFFCH), technical change (TECHCH), pure efficiency change (PECH) and the index of scale efficiency (SECH).

In this way, it can be interpreted whether or not a change that occurs in the total factor productivity index, causing either gain or loss of productivity, is a result of:

(1) changes that have occurred in the inputs and more specifically in emissions of greenhouse gases, in the extraction of mineral resources and in land use, during the period 1990–2011 (see the index of scale efficiency (SECH)). These changes at different stages of economic growth are determined through decoupling indices DI which have as reference points the status of no decoupling, relative decoupling and absolutely decoupling of environmental degradation (greenhouse gas emissions) and resource depletion (material flows, land use) from economic growth.
(2) changes that have occurred in the resource management with impacts to the degree of achievement of optimal resource allocation (see pure technical efficiency index (PECH)).
(3) changes that have occurred in production technology as the result of efforts behind each innovation for resource savings (see technical change index (TECHCH)).

The Malmquist index of total factor productivity growth allows the comparative analysis among the countries and additionally manages to capture the driving forces of productivity gains or losses for the entire EU-13 and for each of the individual EU-13 countries. This index can be used as a tool for exercising preventive environmental policy, in order to ensure sustainable economic growth with signs of qualitative improvement of the product.

Additional file

Additional file 1. The dataset supporting the conclusions of this article is included within the article and its additional file. (http://www.materialflows.net, http://stats.oecd.org/, http://www.eia.gov/countries/data.cfm).

Authors' contributions
All authors contributed extensively to the work presented in this paper. Christina Bampatsou processed the data and performed the analysis. Andreas Dimou was involved in the data analysis, the interpretation of results and the preparation of the manuscript. George Halkos conceived the research, supervised the entire work and commented on the manuscript at all stages. All authors discussed the results and implications.

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Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
The dataset supporting the conclusions of this article is available in the supplementary excel spreadsheet (Additional file 1).

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