



Ecological elasticity, decoupling, and dematerialization: Insights from the EU-15 study (1970–2018)

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ABSTRACT

In the field of decoupling and dematerialization indicators, Ecological Elasticity is suitable for studying the relationship between economic growth and material consumption over extended periods of time. This article aims to analyze decoupling and dematerialization for the EU-15 countries over the period 1970–2018 using the Ecological Elasticity indicator. For this purpose, data obtained through the Material Flow Analysis methodology are used from two different perspectives, territorial and consumption. This allows us to study the differences between the two approaches and to determine the area of utility of each. It is observed that decoupling is a widespread situation across both indicators, but dematerialization is achieved much more frequently in the territorial case. The comparison between methodologies confirms that the dematerialization observed at the territorial level is closely linked to the delocalization of productive activities and the consequent displacement of the environmental burden to other countries. It is proposed that other indicators be used to measure the inter-annual variation of decoupling and to complement Ecological Elasticity, providing a simple and manageable framework on which to design ecological objectives and policies.

1. Introduction

The effects of the Covid-19 pandemic and the war in Ukraine have put the spotlight on the external dependence of developed countries. Physically, two main types of dependence can be distinguished: on the one hand, dependence on the need to import manufactured goods from other parts of the world, due to the inability to produce them locally; on the other hand, dependence on certain natural resources and raw materials. However, the relationship between economic growth and resource consumption has been of increasing interest in recent decades, so that resource efficiency and the reduction of waste and emissions have become a constant in the policy objectives of most governments and institutions. Multiple indicators are used to establish and quantify these targets, some based on the comparison of GDP growth and other environmental or ecological indicators, although GDP is an economic indicator whose ability to represent the evolution of an economy has been widely discussed (Fitoussi et al., 2011; Giannetti et al., 2015; Kubiszewski et al., 2013). Moreover, the evolution of the environment is totally unrelated to what happens with purely economic indicators (Martínez-Alier et al., 2010). The comparison between GDP and environmental impact popularizes the concept of decoupling, which is the

situation where the growth series of GDP and an environmental impact indicator are delinked (Ruffing, 2007), showing an improvement in the efficiency of resource utilization. In the best-case scenario, decoupling would occur because GDP growth is maintained and the impact is reduced, leading to e.g. decarbonization, if CO₂ emissions were measured.

Depending on how it originates, decoupling can be classified in different ways. A widely used classification indicates that when material consumption grows at a slower rate than GDP, relative or weak decoupling occurs; and when material consumption decreases and GDP grows, the decoupling is absolute or strong (Kemp-Benedict, 2018; Krausmann et al., 2017; Ruffing, 2007; Sanyé-Mengual et al., 2019; Song et al., 2019; Tapio, 2005; UNEP, 2011). In the case of absolute or strong decoupling, a fall in material consumption indicates dematerialization. Although the two terms are sometimes used interchangeably, dematerialization only occurs when material consumption is reduced, thus implying a real reduction in material needs (Kemp-Benedict, 2018; Krausmann et al., 2017; Wiedmann et al., 2015). Dematerialization is more appropriate for setting environmental policy objectives than decoupling, as it is the situation that ensures that there is a real improvement in resource consumption. In any case, the study of

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decoupling can also provide interesting information, as it allows the evolution of material consumption to be contextualized with the evolution of the economy.

The study of decoupling and dematerialization indicators does not allow us to delve deeper into the causes of the evolution of material consumption, for which it would be necessary to resort to other indicators and variables. The relationship between material consumption and economic growth is complex and is conditioned by multiple aspects that influence each variable. Nevertheless, the concept of decoupling is of great interest due to its simplicity and ease of interpretation (Ruffing, 2007). In its interest is its ability to indicate the relationship between economic growth and resource consumption in a condensed form, allowing basic predictions to be made about their evolution. The most straightforward way to study both decoupling and dematerialization is to compare the rates of change of material consumption and GDP. However, condensing the graphical information into a single indicator is much more operational for setting and measuring targets or making inter-territorial comparisons. To do so, the indicators used must comply with several principles that allow them to be considered as good indicators. According to Jørgensen (2016), a good ecological indicator should be manageable, sensitive to small variations in environmental stress, applicable to large geographic areas, applicable in different territories and ecological settings, and quantitative.

The study of the relationship between GDP and environmental impact requires a data input that is simple to obtain in the case of GDP, but more complex in the case of environmental impact. One of the methodologies that allow the environmental impact to be approximated is the Analysis of Material Flows (MFA), a method based on the theories of socioeconomic metabolism to provide information on the material flows generated by the socioeconomic activity of a territory. (Ayres & Simonis, 1994; Fischer-Kowalski & Weisz, 1999). Material flows are the physical connection between human societies and the environment, so they are a good measure of the pressure that human activities put on nature (Eisenmenger et al., 2016).

In this context, the group of countries that make up the EU-15 represent a paradigmatic case of economies with a low endowment of natural resources and which, moreover, have lost part of their productive capacity in recent decades in favour of the service sector. External dependence has a relatively positive side for these countries, which is that it allows them to avoid the environmental impact linked to certain production processes. This puts them in an advantageous position when it comes to reducing the impact of their economic activity. Moreover, the European Union is a pioneering institution in the field of ecological transition policies. The evolution of environmental indicators in these countries is of particular interest as it allows the effects of these policies to be assessed.

In view of these issues, the aim of this research is to analyse decoupling and dematerialization in the EU-15 countries through Ecological Elasticity, comparing the results of the territorial method and the AFM consumption method. This shows the relevance of Ecological Elasticity as a suitable indicator for defining and monitoring ecological and environmental policy objectives and for analyzing the relationship between economic growth and material consumption. This indicator is particularly suitable for studying this relationship over long periods of time, allowing basic conclusions to be drawn in a straightforward and simple way. This indicator is also compared with other similar indicators used by different institutions, such as the Tapio Decoupling Index, the Decoupling Factor, and the Decoupling Ratio, in order to determine the advantages and disadvantages of each indicator. In this research, indicators of material consumption are used, so that we would speak of a situation of dematerialization, i.e., a reduction in material consumption in absolute terms, while maintaining a growing GDP (Schandl et al., 2018; UNEP, 2011). At the same time, the differences between each method of data collection and the advantages and disadvantages of each are shown. The result is the proposal of a framework for the analysis of decoupling and dematerialization through the analysis of the EU-15

case. The comparison of Ecological Elasticity with other similar indicators of decoupling is a novel contribution, even more so when it is carried out by comparing the different perspectives of the MFA, resulting in information of great relevance for policy makers.

The selection of the group of countries that made up what was known as the EU-15 is due to the reasons described above, which, together with the relatively homogeneous characteristics of their economies, allows for an analysis of great interest. Moreover, it is exportable to other developed economies that have a territorial and political structure similar in many respects to that of the European Union, such as the United States. And although the UK is no longer a member of the EU, it does not negatively affect the analysis because it did apply EU policies during the period under analysis. Similarly, some of the countries analysed were not part of the EU-15 during the first years of the study, but it is equally interesting to understand them over the entire period 1970–2018. Although the most significant structural changes and implementation of measures have taken place in the last two or three decades, the aim is to obtain a solid context, which allows for a proper assessment of the historical trends of the indicators.

This research produces different novel contributions in the field of decoupling and dematerialization. On the one hand, the comparison of the indicators most used to measure decoupling by institutions such as the United Nations, which makes it possible to assess the advantages and disadvantages of each of them and to define their scope of use more appropriately. The decoupling of economic growth from environmental impact is a widely studied issue (Cohen et al., 2018; Kemp-Benedict, 2018; Song et al., 2019, 2020), but almost always through a territorial approach. The comparison of the territorial and the consumption approach is therefore an interesting contribution to the debate on decoupling, as the difference between these methods is an important part of the discrepancy in the results of other studies. The comparison between methods is an issue previously addressed in other studies (Karakaya et al., 2021; Sanyé-Mengual et al., 2019), but this paper presents a longer time span and recently updated data. On the other hand, environmental impact is approached from an input perspective, through resources extracted from nature, rather than through emissions and waste, a more generalised form. Although both ways measure the pressure of economic activity on nature, an input perspective focuses on the costs of economic growth in terms of resource availability, an increasingly pressing issue today, especially in the EU-15 countries.

2. Methods and data

2.1. Material flows analysis

Regardless of the type of indicator used, a quality data source is necessary to draw sound conclusions. The AFM is able to provide consistent environmental impact data that fulfils this function (Fischer-Kowalski & Amann, 2001). The AFM is a methodology originally developed by Ayres and Kneese (1969) for the study of economic externalities, and subsequently updated and improved in a process that continues to this day (Ayres & Ayres, 1998; Daniels, 2002; Daniels & Moore, 2001; EUROSTAT, 2018; Fischer-Kowalski et al., 2011; Fischer-Kowalski & Haberl, 1998).

Depending on how responsibility for the environmental impact generated by physical trade flows is allocated, the AFM can be elaborated in different ways. This paper considers the territorial or production approach and the consumption approach. The territorial perspective assigns to the material consumption of each territory all the resources used in domestic production processes, discounting the weight of exported materials and adding the weight of imported ones (EUROSTAT, 2018; Krausmann et al., 2017; Piñero et al., 2019; Schandl et al., 2016, 2018). The consumption perspective assigns to each territory the resources used to produce the goods consumed by its final demand, regardless of where the production of these goods has taken place (Dittrich et al., 2012a; Schandl et al., 2018; Wiedmann et al., 2015). By

far the most widespread method is the territorial or production method, but in a context of globalization of production chains, it is limited in terms of properly allocating responsibility for the environmental impact linked to trade, something that is possible through the consumption method (Dittrich et al., 2012a; Piñero et al., 2019; Schandl et al., 2018; Wiedmann et al., 2015).

The AFM allows for two indicators of material consumption, depending on the perspective used to determine responsibility for material consumption. Both indicators start from Domestic Extraction (DE), which is the sum of all materials, biotic and abiotic, extracted from nature and used in some economic activity (EUROSTAT, 2018; Krausmann et al., 2017; Schandl et al., 2018). If physical imports are added to the DE and physical exports are deducted, the result is material consumption. The difference between the material consumption of the territorial method and that of the consumption method lies in the way the materials exchanged in international trade are accounted for. In the territorial method, trade flows only represent the weight of the final goods traded, resulting in Domestic Material Consumption (DMC) (Ayres & Ayres, 1998; Daniels & Moore, 2001; Dittrich et al., 2012b; EUROSTAT, 2018; Schandl et al., 2018). In this way, the DMC provides an approximation of the environmental impact occurring within each territory (EUROSTAT, 2018; Schandl et al., 2018).

The physical trade flows of the consumption method comprise all materials used to produce the final traded goods, providing the Material Footprint (MF), which indicates the materials used to produce the goods consumed by a territory's domestic demand, regardless of where they were produced (Arto et al., 2012; Dittrich et al., 2012a; Schaffartzik et al., 2015; Schandl et al., 2018; Wiedmann et al., 2015). The Material Footprint is therefore an approximation of the environmental impact linked to final consumption in each country, regardless of where it actually occurs (Dittrich et al., 2012a; EUROSTAT, 2018; Schandl et al., 2018; Wiedmann et al., 2015).

Calculating the difference between the Material Footprint and the DMC gives the Indirect Trade Flows (ITF), which correspond to the consumption of materials linked to a country's final demand in the rest of the world (Dittrich et al., 2012a). In other words, it allows to check the burden that one country shifts to the rest of the world.

2.2. Indicators to measure decoupling and dematerialization

The study of the decoupling of economic growth and environmental impact dates back to the 1990s. However, it is in the first decade of the 21st century that it became more interesting, when organisations such as the OECD began to develop decoupling indicators (OECD, 2002). Later, Tapio (2005) developed an indicator and a methodology that became the most widespread way of assessing decoupling. Since then, studies have been carried out on the decoupling between growth and different magnitudes, such as environmental impact or energy consumption (Cohen et al., 2018; Dong et al., 2021; Kan et al., 2019; Song et al., 2020; Wang et al., 2019). Work in the field of decoupling is not only differentiated by the different indicators used for the study, but also by the methodological approaches used to obtain the data. Thus, it is important to differentiate the conclusions obtained when the data have a production or territorial orientation from those drawn from work using an approach capable of capturing the effect of international trade (Piñero et al., 2019, 2020; Pothén, 2017). The latter approach is becoming increasingly important, due to the importance of international trade and the globalisation of production chains (Kan et al., 2019).

The conclusions regarding decoupling are very different depending on the indicators and approaches used. In the field of environmental impact, and in particular material consumption, decoupling contributes to the debate on dematerialisation. In this debate, a prominent position is taken by the research of Panayotou (1995), which indicates that above a certain level, economic growth reduces environmental impact, giving rise to the so-called Environmental Kuznets Curve (EKC). Under the EKC hypothesis, multiple studies have been carried out that point to the

existence of relative decoupling, but absolute decoupling or dematerialisation do not appear in practically any case from a consumption perspective (Arshad Ansari et al., 2020; Pothén & Welsch, 2019; Steinberger et al., 2010, 2013). It is worth noting that even in studies where the same approaches are used, discrepancies are common if different environmental impact indicators (e.g., CO2 emissions and material consumption) are used. This is because neither CO2 emissions represent the totality of environmental impact, as they do not account for all waste, nor are material consumption indicators able to account for all materials mobilised by human activity.

The decoupling indicators presented below are of great interest for simple and direct comparisons between different territories and using different perspectives or indicators. However, behind decoupling and dematerialization there are multiple factors that cannot be considered in a single indicator. At the same time, another of the debates surrounding decoupling is the appropriateness of using GDP as the main indicator, as it is a highly questioned indicator in its capacity to measure well-being (Fitoussi et al., 2011; Wang et al., 2019). At the same time, GDP can be an ecological indicator of interest when it has a stable relationship with environmental impact, acting as a predictor of environmental impact (Mulder et al., 2021).

Below are some of the most used indicators of decoupling in research and by different institutions, which are the ones that will be used to develop the central analysis of this paper later.

2.2.1. Decoupling factor and decoupling ratio

The Decoupling Factor (DF) is an indicator used by the OECD (2002) and is constructed as follows (Ruffing, 2007):

$$DF = \frac{(EP/DF)_t}{(EP/DF)_{t_0}} \quad (1)$$

Where EP stands for Environmental Pressure and DF for Driving Force. In the case of this research:

$$DF = \frac{(MC/GDP)_t}{(MC/GDP)_{t_0}} \quad (2)$$

Where MC is Material Consumption. If the value of the indicator is <1, decoupling has occurred in the period analyzed, otherwise it has not. In order to obtain better results in terms of graphic visualization, it is common to use the Decoupling Ratio (DR), which is obtained by:

$$DR = 1 - \frac{(MC/GDP)_t}{(MC/GDP)_{t_0}} \quad (3)$$

The DR indicates that decoupling exists when its value is greater than zero, while it will not exist if it is equal to zero or negative. This indicator has the disadvantage that it does not provide information on whether the decoupling is relative or absolute, so it does not provide information on whether dematerialization exists. Moreover, the quality of the information worsens the longer the time periods considered, as the information and variability of all periods between the initial and the final one is omitted. It is most useful for analyzing period-by-period variability.

2.2.2. Tapio decoupling index

The Tapio Decoupling Index (TDI) is based on the elasticity of a factor A with respect to a factor B, and is therefore obtained by the quotient of the variation of factor A and the variation of factor B (Tapio, 2005). In the case of material consumption, this would be the ratio of the change in material consumption to the change in GDP:

$$TDI = \frac{\% \Delta MC}{\% \Delta GDP} \quad (4)$$

In a more developed form, it could be expressed as:

$$TDI = \frac{(MC_t - MC_{t_0}) / MC_{t_0}}{(GDP_t - GDP_{t_0}) / GDP_{t_0}} \quad (5)$$

TDI is widely used by institutions such as UNEP (2011) to measure environmental impacts. It has the advantage of being able to assess both decoupling and dematerialisation. In addition, each broad category of decoupling can be disaggregated into subcategories based on the value of the TDI, resulting in a very comprehensive and extended framework for decoupling analyses (Dong et al., 2021; Song et al., 2019, 2020; Yu et al., 2017) as set out in Table 1.

The concept of negative decoupling is of interest to classify those situations in which the decoupling occurs in reverse, i.e., it is material consumption that grows above GDP. It is also of interest to distinguish situations of recessionary decoupling, as this situation indicates that there is a fall in economic activity rather than an improvement in physical dependence. It is unusual to have many consecutive periods of recession, so that sub-categories that include GDP decline are not very applicable in the long run. However, in short time intervals or in annual analyses it is very interesting, as it complements the information that can be obtained from the TDI value.

Among the disadvantages of this indicator, it can be pointed out that, when analyzing periods covering several years, the information and variability of the intermediate periods is omitted, in the same way as for DF and RD. Although it is useful for studying period-to-period variation, it can give rise to very scattered results, especially when there are very small variations in GDP.

2.2.3. IPAT and STIRPAT: Ecological Elasticity

Ecological elasticity is based on the concept of elasticity commonly used in economics and refers to the percentage change in the dependent or explained variable that causes a unit change in the independent or explanatory variable. In this sense, the approach does not differ much from the indicator proposed by Tapio (2005), although their origin and conceptual approach is completely different. If a residual error term is added to the elasticity formula, it is possible to obtain a stochastic equation that can be estimated with multiple observations over time or cross-section, using common statistical techniques such as regression (York et al., 2003).

The origin of Ecological Elasticity goes back to the IPAT model, one of the first mathematical formulations designed to assess the impact of human activity on the environment. It is the result of the work of researchers from different fields of study, such as biology, ecology and environmental science (Fischer-Kowalski & Amann, 2001). The first contributions come from the works of Ehrlich and Holdren (1971; 1974) and Commoner (1972), who shaped the first formulations of the IPAT. The first formulation of the IPAT had two factors, population and per capita environmental impact, expressed as a function of population (Ehrlich & Holdren, 1971). It was later expanded and specified as the product of three components: population (P), affluence or wealth per capita (A) and technology (T), giving rise to the expression $I = PAT$

Table 1 Framework for the assessment of decoupling.

Category	Subcategory	GDP	DMC or MF	TDI
Decoupling	Strong Decoupling (SD)	>0	<0	≤0
	Weak Decoupling (WD)	>0	>0	0.8 ≥ TDI > 0
Negative Decoupling	Recessive Decoupling (RD)	<0	<0	1.2 >
	Expansive Negative Decoupling (END)	>0	>0	>1.2
	Strong Negative Decoupling (SND)	<0	>0	≤0
	Weak Negative Decoupling (WND)	<0	<0	0.8 ≥ TDI > 0
Coupling	Recessive coupling (RC)	<0	<0	1.2 ≥ TDI > 0.8
	Expansive coupling (EC)	>0	>0	1.2 ≥ TDI > 0.8

Source: adapted from Tapio (2005).

(York et al., 2003). The specification of the IPAT implies that each factor has an influence on the others, as they multiply each other. Therefore, even if only one of the factors is changed, the environmental impact will change as a result of the interaction between all of them (York et al., 2002). This interconnectedness between factors makes the concept of plasticity, which refers to the potential of variables to move in different directions as a result of historical processes or policy interventions, particularly relevant (York et al., 2002, 2003). Plasticity consists of the range of potential variation of each element and the ratio or rate at which it varies, i.e., the speed at which it can change. Estimating plasticity is relatively straightforward for population but is much more complex for inflow and technology.

The strengths of the IPAT model are the quality of its specification and the simplicity with which it is generalizable, making it a very useful basis on which to build theories of environmental impact (Dietz & Rosa, 1994; Fischer-Kowalski & Amann, 2001; York et al., 2003). Its main limitation is that it is a mathematical identity that assumes proportionality in the relationship between the factors, while the known factors determine the unknown factors, so it is not suitable for testing hypotheses (Fischer-Kowalski & Amann, 2001; York et al., 2003).

The reconversion of the IPAT model to a stochastic model, known as STIRPAT, opens the door to many more utilities, including the testing of hypotheses, the possibility of extracting indices for individual indicators or the incorporation of the growth rate of variables into the analysis (Dietz & Rosa, 1994; York et al., 2003). Thus, the model would be specified as shown in the equation (6):

$$I_i = aP_i^b A_i^c T_i^d e_i \tag{6}$$

The coefficient a represents the ordinate at the origin, b , c , and d are the coefficients that must be estimated to know the effect of P, A and T on I and e is the error term. The subscript i indicates that I, P, A, T and e vary between observations (Dietz & Rosa, 1997; York et al., 2003). It is common for T to be omitted from the model and included in the error term, due to the difficulty of properly delineating what this factor should cover (Dietz & Rosa, 1997; York et al., 2003), with the model taking the following form.

$$I_i = aP_i^b A_i^c e_i \tag{7}$$

Furthermore, for ease of estimation and hypothesis testing, it is common for equation (2) to be expressed in logarithmic form:

$$\log I = a + b(\log P) + c(\log A) + e \tag{8}$$

Equation (8) is the basis from which the indicators used in this paper are extracted.

One of the advantages of the stochastic version of the IPAT is the possibility of extracting indices for any of the factors in isolation, allowing the individual effects of each factor to be studied. The effect of each factor on the environmental impact is called ecological elasticity, a measure that is related to the concept of plasticity. While plasticity refers to the potential for change in the factors that determine environmental impact, ecological elasticity refers to the sensitivity of environmental impact to a change in any of these factors (York et al., 2003). Thus, ecological elasticity allows for a precise interpretation of the effect of IPAT factors on environmental impact.

In this paper, we call the ecological elasticity the ecological elasticity of inflow. To obtain it, it is sufficient to use the data in per capita terms and shift T to the error term, so that the following equation is obtained:

$$\log I = a + c(\log A) + e \tag{9}$$

The coefficient c is equivalent to the ecological elasticity of inflow and the target of the estimate. This coefficient is interpreted as a measure of the strength of the relationship between income and environmental impact (Steinberger et al., 2013; York et al., 2003).

Ecological elasticity makes it possible to determine the degree of coupling or decoupling that exists between them and, therefore, whether

dematerialization occurs in a territory. The interpretation of the coefficient c is analogous to that of Tapio's decoupling coefficient (see Table 1).

2.3. Data

The data related to the Material Flows Analysis methodology comes from the Global Material Flows Database. (UNEP, 2022)¹ de United Nations Environment Programme. The material consumption indicators, the DMC and the Material Footprint are obtained from this database. GDP data based on 2010 are obtained from the World Bank.

The analysis is carried out on the set of countries that form part of the European Union 15. These countries form a fairly homogeneous and representative group of developed economies. Some of the key characteristics they share are the high degree of tertiarisation of their respective economic structures, a high level of development and the promotion of important measures to reduce environmental impact, in line with the European Union's environmental policy. The time interval analysed is from 1970 to 2018. The main reason for the selection of this interval is the availability of data, with the year 2019 being omitted as it contains estimates among the data.

2.4. Limitations and possible extensions of the analysis

The ecological elasticity is an estimate that assumes a linear relationship between economic growth and material consumption, so it does not always provide a good fit. However, the fit improves the more the two variables are related, irrespective of the direction of the relationship, so the usefulness of the ecological elasticity is evident. Ecological Elasticity is not suitable for measuring variation over short periods of time, for example on a year-on-year basis, so complementary decoupling indicators such as the TDI are proposed.

One of the most interesting extensions would be the inclusion of heterogeneous countries, with different characteristics and levels of development, which would broaden the conclusions of this article. In addition, extending the period analysed would contribute to the robustness of the conclusions, but this is subject to the availability of data. On the other hand, it might be of interest to introduce a quadratic term in the model, which would allow testing the hypotheses of the Environmental Kuznets Curve, although it does not seem likely to be fulfilled in view of the results of this research.

3. Results and discussion

Through a preliminary descriptive analysis of the data, some important issues can be identified. Fig. 1 shows the evolution between 1970 and 2018 of the DMC, the Material Footprint and GDP.

The first conclusion that can be drawn is that there is a decoupling throughout most of the period analyzed. Moreover, the DMC and the Material Footprint always evolve in a very similar way, although the Material Footprint is always found to be higher. An important point of divergence is that through the territorial approach (DMC) there are several phases of absolute decoupling or dematerialization, whereas through a consumption approach this situation is never reached. These phases coincide with moments when GDP decreases or grows to a lesser extent, although in the last years of the graph GDP seems to recover and DMC is maintained. The Material Footprint, although not decreasing, does show a trend towards lower growth.

On the other hand, ITF are evolving at a very high rate, higher than GDP, albeit with an irregular trend after the large drop coinciding with the 2008 Crisis. This implies that the EU-15 countries, on average, have substantially increased the burden shifted to the rest of the world, which can be interpreted as a greater dependence on material consumption in

the rest of the world. This is a consequence of the tertiarization of the economic structure and the processes of delocalization of production that have developed over the last decades (Arto et al., 2012; Dittrich et al., 2012a; Wiedmann et al., 2015).

Fig. 2 shows the per capita ITF for each EU-15 country.

All the countries analyzed have positive ITFs, implying that they all shift environmental load to the rest of the world. This is particularly noticeable in Belgium, the Netherlands and Ireland, although the tendency is for countries further north to shift a greater burden. Differences in the economic structure of the EU-15 countries play an important role in this issue. In the countries of the South, the primary sector, and other extractive sectors such as those linked to construction have a higher weight than in the case of the countries of the North. This is especially noticeable in the smaller countries, which have a very contained primary sector. At the same time, small and developed countries tend to have a very low primary sector presence and economies in which the tertiary sector, and more specifically the financial sector, has a large weight. It is therefore to be expected that the greatest differences between methods occur in countries with these characteristics.

3.1. Tapio decoupling index, decoupling factor and decoupling ratio

In this section the results for DI, DF and DR are shown and analyzed. Fig. 3 plots the evolution of DF for DMC and Material Footprint over the period 1970–2018 for the EU-15. For most of the period analyzed there is decoupling, although not by much, for both variables and the difference between them is quite modest.

Through this indicator it is not possible to know if there is dematerialization, so it can only be concluded that GDP has grown more than material consumption, and it is necessary to resort to the data series to determine the type of decoupling.

DR is more suitable for cross-country comparisons, so Fig. 4 shows the evolution over the period 1970–2018 for all EU-15 countries.

In the period 1970–2018 all countries in the EU-15 as a whole show decoupling for both the DMC and the Material Footprint. The level of decoupling is significantly higher in the case of the DMC, because of the allocation of greater responsibility for resource consumption through the Material Footprint. Again, it is not possible to distinguish whether the decoupling is relative or absolute and therefore it cannot be analyzed whether dematerialization exists. Both DF and DR are indicators that are incomplete from an ecological perspective, as the targets should focus primarily on dematerialization. Moreover, when they are calculated for such a long period, many periods in which the economy goes through different cycles are omitted, so that the result is not very faithful to the real evolution during that time interval.

The DI has the advantage of being able to identify the type of decoupling. Fig. 5 shows the evolution of the DI for the DMC and the Material Footprint for the EU-15 over the period 1970–2018.

Significant variability can be observed throughout the series. It is strongly influenced by the extreme values stemming from the 2008 Crisis. The DMC is more often found in decoupling and dematerialization values (below 1 and 0, respectively), while the Material Footprint is more often found in coupling or rematerialization values (above 1). The variability of the series makes it difficult to interpret the data and draw robust conclusions, as well as to apply the extended classification in Table 1. This indicator can also be calculated for longer time intervals, as is done in Fig. 6.

For the period 1970–2018 there are important differences between the territorial and the consumption perspective. Through the DMC, up to 7 countries reach absolute decoupling and so does the EU-15 average. On the other hand, through the Material Footprint, only Italy and Germany reach dematerialization values. This is a good illustration of the importance of the selection of one method or another, as it clearly conditions the result.

When applying the extended classification in Table 1, it can be assumed that in the period under consideration GDP has grown in all EU-

¹ <https://www.resourcepanel.org/global-material-flows-database>.

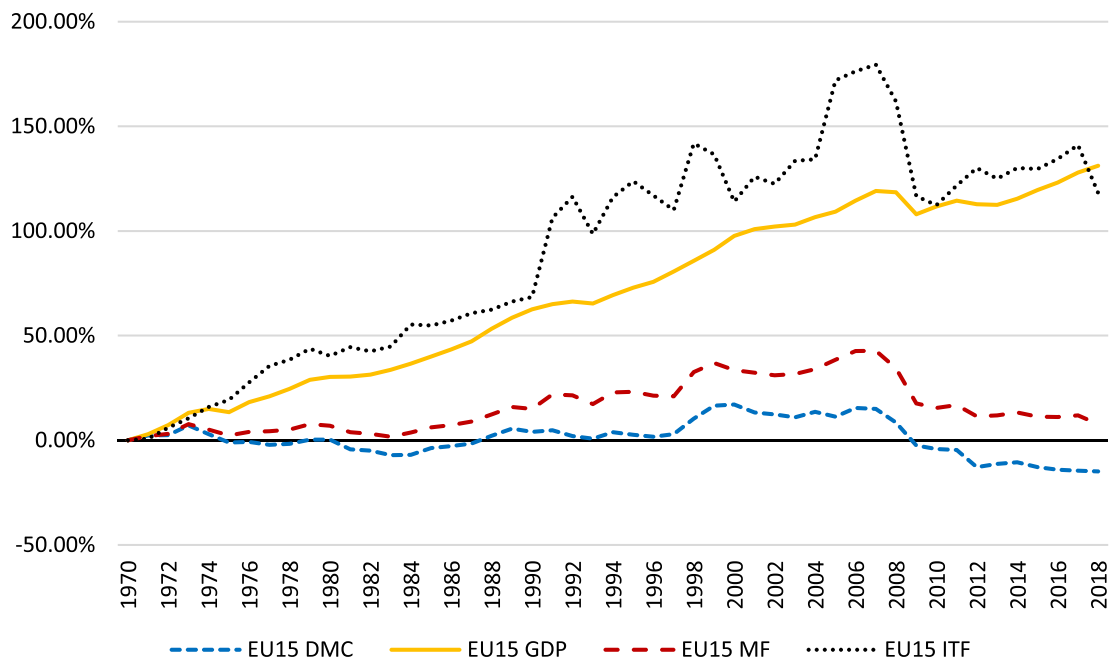


Fig. 1. Rates of change of DMC, MF, FTI and GDP for the EU-15.

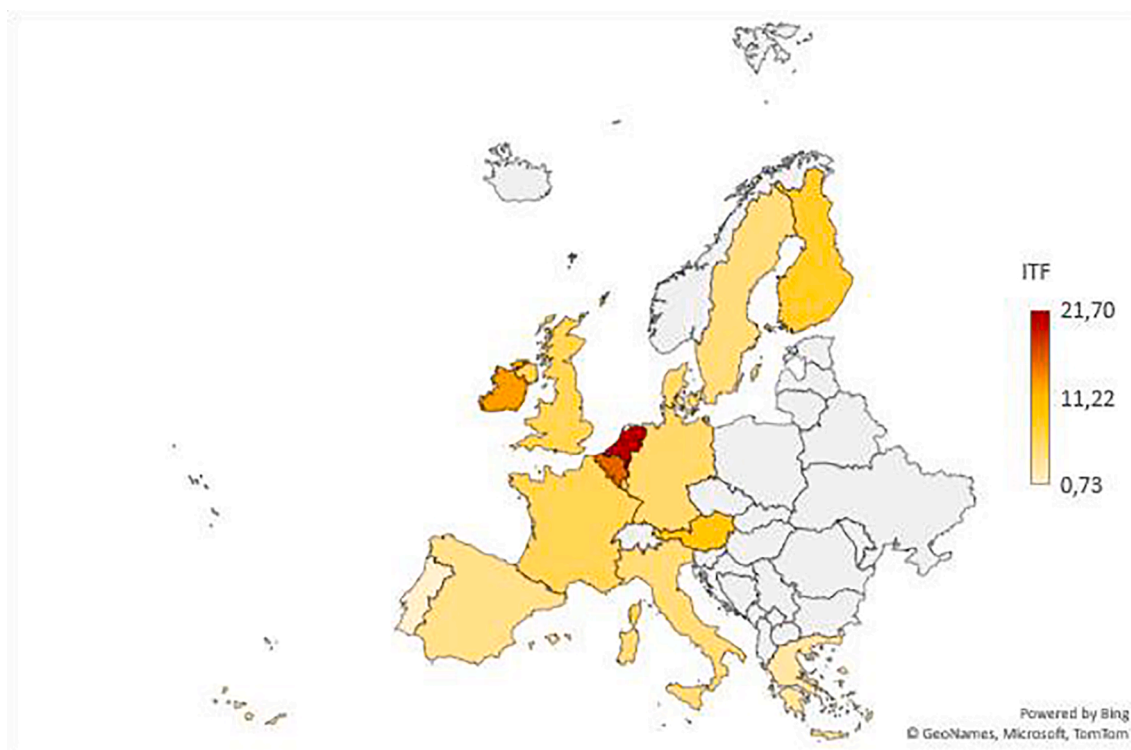


Fig. 2. ITF by country, tonnes per capita, 2018.

15 countries. Therefore, situations where GDP decreases (SND, WND, RC, RD) can be excluded. In terms of DMC, all countries that do not reach absolute decoupling are in weak decoupling (WD). The same situation occurs in the case of the Material Footprint, with the difference that there are far fewer cases of dematerialization.

The great advantage of DI over DF and DR is the possibility of knowing the type of decoupling and, therefore, whether there is dematerialization. For long time intervals it has the same disadvantage, caused by the omission of information from the intermediate periods,

which conditions the result. On the other hand, this indicator may be of interest for analyzing recent developments, as an annual reference indicator or even for shorter time intervals.

3.2. Ecological elasticity

Once a first approximation and analysis of the data has been carried out based on the indicators proposed for purchasing with Ecological Elasticity, Tables 2 and 3 present and analyze the results for Ecological

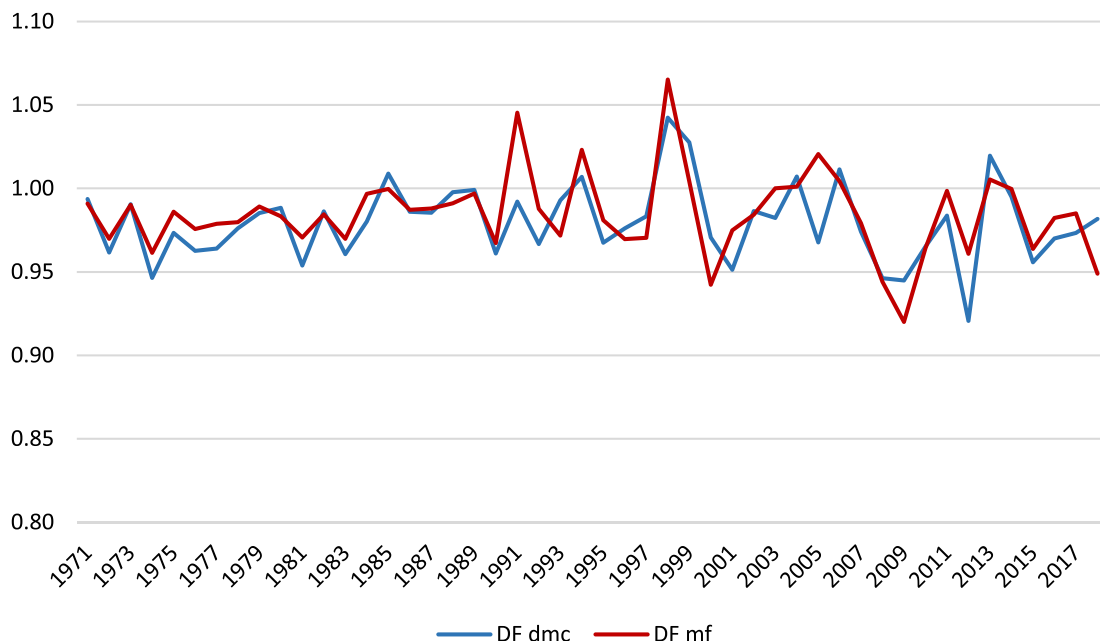


Fig. 3. DF for DMC and MF, 1970–2018.

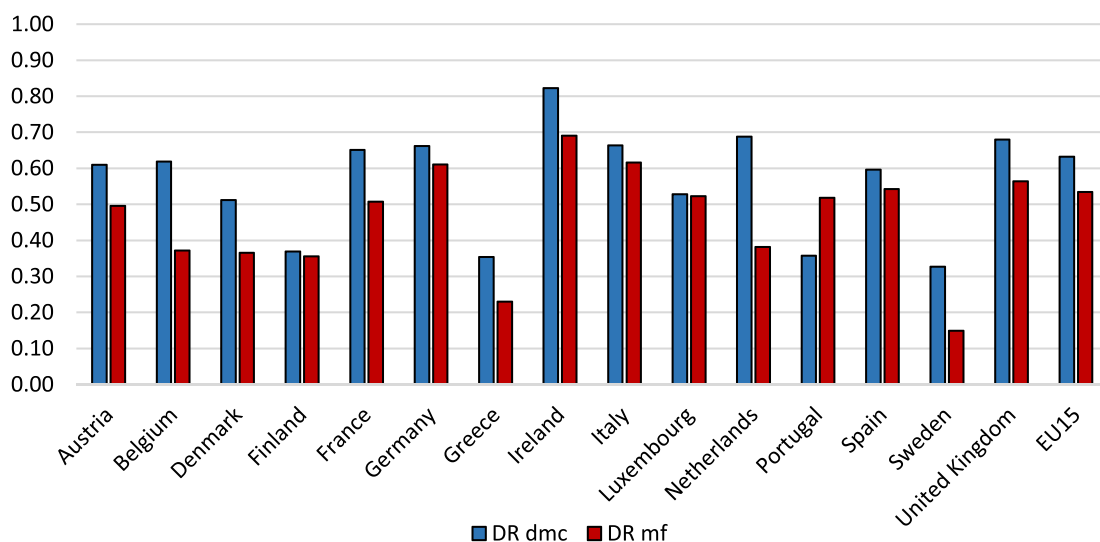


Fig. 4. DR by country, DMC and MF, 1970–2018.

Elasticity using the territorial and consumption methods.

By means of Ecological Elasticity, substantial differences between the territorial method and the consumption method can also be seen. Analyzing through the DMC, up to 5 countries are at dematerialization values (highlighted in green) and all except Portugal and Greece (EC, highlighted in orange) show decoupling. In addition, the EU-15 also shows dematerialization, albeit very little. Bearing in mind that the DMC is a good approximation of the impact occurring in the territory of each country, what can be interpreted from these results is that many of the EU-15 countries and the average for the EU-15 manage to reduce the environmental impact on their territory as their GDP grows. This is consistent with the evolution of the economic structure of developed economies in recent decades, which has become increasingly specialized in the service sector. In countries that achieve dematerialization, the processes of productive delocalization and economic financialization are very important, as material consumption is transferred to other parts of the world and the economy grows increasingly disconnected from real

magnitudes (Davis & Kim, 2015; Schwan, 2017). It can be seen in Fig. 1 how the ITF have increased considerably between 1970 and 2018, which points to an increased dependence on production in other countries. At the same time, it is easy to see a “size effect” in countries such as Belgium, the Netherlands, or the United Kingdom. The material consumption of these countries is softened as a result of a lower share of long-distance transport and agricultural activities (Weisz et al., 2006).

Focussing on the Material Footprint, the situation changes substantially. In this case, although almost all countries achieve weak or relative decoupling, only Germany achieves dematerialization. Sweden and Portugal are at EC values (orange) and Greece has Negative Coupling (red). In the case of Greece and Portugal, the stronger link between GDP growth and DMC can be associated with low levels of development and efficiency during the first part of the studied interval (this implies a significant physical investment in infrastructure throughout this period, for example), and with a relatively high presence of primary sector related activities. In Sweden, extractive activities related to fossil fuels

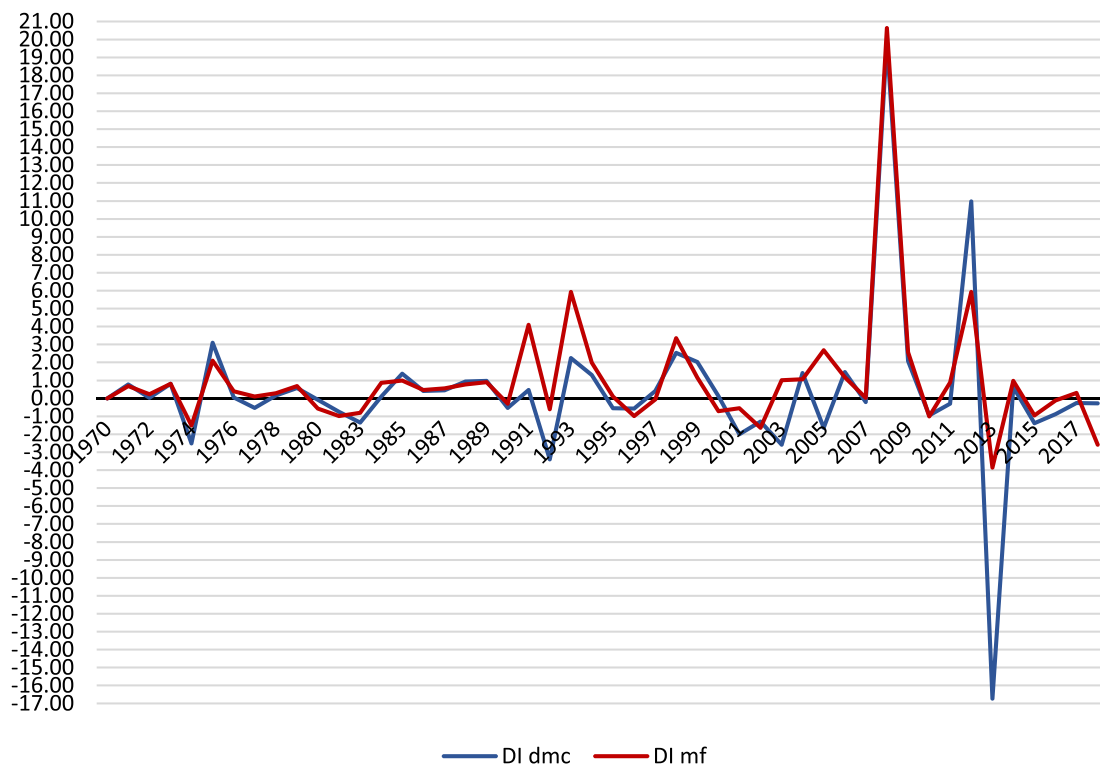


Fig. 5. DI for DMC and Material Footprint, EU-15, 1970–2018.

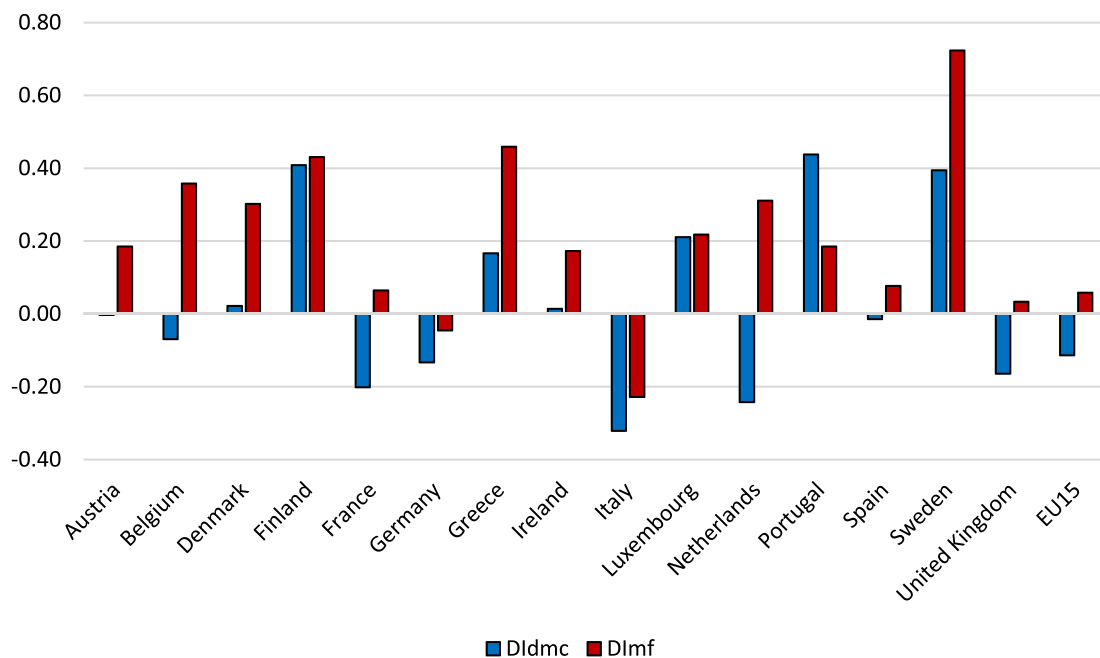


Fig. 6. DI for DMC and Material Footprint by country, 1970–2018.

have a higher impact than usual in the rest of Europe, as well as activities related to wood.

Several factors lie behind Germany’s dematerialization. Notably, although it has lost industrial capacity, it still retains a significant part of its industry (De Ville, 2018), while at the same time it has high efficiency standards in the agricultural sector and has managed to reduce its consumption of fossil fuels significantly. It is true that it maintains a high dependence on raw materials from the rest of the world (Schüller et al., 2008), but the maintenance of local industry favours greater efficiency

in the final consumption of resources. This is because importing goods from less developed countries usually implies higher material consumption, due to the need for transport and lower efficiency standards.

Regarding the advantages and disadvantages of Ecological Elasticity, the strong point of this indicator is undoubtedly its ability to capture all the variability of the period analysed, resulting in a representative value of the relationship between GDP and material consumption. The indicator loses explanatory power when the relationship between these variables is not very strong, but this is easily interpretable. The major

Table 2
Ecological Elasticity model results for the DMC.

Country	Ecological Elasticity	t-statistic	Error	R ²
Austria	0.17225	4.73***	0.0364	0.308
Belgium	-0.3321	-5.984***	0.0555	0.4204
Denmark	0.21619	2.834**	0.0763	0.1277
Finland	0.73709	10.172***	0.0725	0.681
France	-0.19039	-3.91***	0.0487	0.2294
Germany	-0.18677	-5.402***	0.3457	0.3699
Greece	0.8685	7.617**	0.1140	0.5429
Ireland	0.31479	4.417***	0.0713	0.2783
Italy	0.08032	0.71	0.1132	-0.01044
Luxembourg	0.21542	2.315	0.0931	0.08328
Netherlands	-0.36171	-6.552***	0.0552	0.4662
Portugal	1.0213	8.786**	0.1162	0.6135
Spain	0.5341	4.783***	0.1117	0.313
Sweden	0.5535	6.604***	0.0838	0.4703
United Kingdom	-0.30564	-5.898***	0.0518	0.4131
EU-15	-0.001059	-0.021	0.0493	-0.02127

Source: own elaboration based on data from Global Material Flows Database (UNEP, 2022). * Denotes coefficients whose value is different from 0 at a 5% significance level. ** denotes coefficients whose value is different from 0 at a significance level of 1%. *** denotes coefficients whose value is different from 0 at a significance level above 1%.

Table 3
Ecological Elasticity model results for the Material Footprint.

Country	Ecological Elasticity	t-statistic	Error	R ²
Austria	0.37268	16.4720***	0.02263	0.8492
Belgium	0.49304	13.2680***	0.03716	0.7848
Denmark	0.72007	9.1440***	0.07875	0.6325
Finland	0.37268	16.4720***	0.02263	0.8492
France	0.26342	7.0130***	0.03756	0.5009
Germany	-0.06506	-1.3640	0.04771	0.0176
Greece	1.2141	13.5000***	0.08996	0.7905
Ireland	0.5073	7.0690	0.07176	0.505
Italy	0.2537	2.4880*	0.102	0.09756
Luxembourg	0.55364	11.7190***	0.04724	0.7396
Netherlands	0.58698	11.4900***	0.5109	0.454
Portugal	0.86806	9.6150***	0.09028	0.6558
Spain	0.48598	6.3960***	0.07598	0.454
Sweden	1.0990	21.2300***	0.05176	0.9036
United Kingdom	0.15539	3.5100***	0.04427	0.1908
EU-15	0.28465	6.6950***	0.04252	0.4772

Source: own elaboration based on data from Global Material Flows Database (UNEP, 2022). * Denotes coefficients whose value is different from 0 at a 5% significance level. ** denotes coefficients whose value is different from 0 at a significance level of 1%. *** denotes coefficients whose value is different from 0 at a significance level above 1%.

shortcoming of this indicator is that it is not suitable for studying short-term developments, e.g., on an annual basis. However, its ability to make short and medium-term forecasts is of interest, even if these are not very refined estimates.

3.3. Key issues and policy implications

The comparison between the different indicators allows to determine which of them is more suitable for each use. Thus, Ecological Elasticity is clearly the best one to analyze decoupling and dematerialization over large data intervals, condensing a large amount of information into a single data point. It is the most suitable indicator of those described to

study the historical relationship between GDP growth and material consumption or any other similar ecological indicator. The graphical analysis of the rates of change is a good complement in this task, as it allows to study specific periods easily and to investigate the behaviour in different economic cycles. On the other hand, DI is useful to study the evolution of decoupling and dematerialization in the short term, e.g. on an annual basis. For this function, it is of particular interest when used in conjunction with the extended decoupling classification set out in Table 1, providing a very direct, clear and easy to interpret indicator of the (for example) year-on-year change in decoupling. In any case, the design of ecological policies should be based on a much deeper study and a much wider range of indicators and variables. Ecological Elasticity and DI are presented as very condensed indicators of information, useful to facilitate decision making for non-specialists in the area of ecological economics.

On the other hand, the different indicators have been showing a clear trend regarding the differences between the DMC and the Material Footprint. It is evident that the DMC is more contained in the EU-15 countries, with dematerialization being achieved much more frequently. This should be interpreted as the EU-15 countries achieving a clear decoupling from the environmental impact occurring within their territories (Krausmann et al., 2017; Schandl et al., 2018). The decoupling indicators fed with territorial data therefore make it possible to study the evolution of local impact.

The Material Footprint does not evolve as favourably. Although the general trend is towards relative decoupling, dematerialization is an exceptional situation. Beyond the case of Germany, the EU-15 countries do not manage to reduce the number of resources their economies need to sustain themselves. It is true that, from the graphical analysis, the trend points to a reduction in the rate of growth, so it will be interesting to see how it evolves in the coming years. In any case, the reduction in material consumption is not yet a real situation, as it is generally linked to the displacement of environmental burdens to other countries through production relocations. This can be seen through the difference between the Material Footprint and the DMC, which is growing at a high rate throughout the time researched (see Fig. 1). Therefore, the use of the DMC to assess the evolution of material consumption can lead to erroneous conclusions, and the Material Footprint should be used for this purpose (Krausmann et al., 2017; Piñero et al., 2019; Schaffartzik et al., 2015; Wiedmann et al., 2015).

It should be noted that, given the relationship between GDP and material consumption that exists in the EU-15 countries, this can be a good predictor of the evolution of environmental impact and an ecological indicator of interest (Mulder et al., 2021). It is therefore urgent to focus efforts on decoupling the trend in GDP from the trend in environmental impact, or to propose alternatives that allow economic and social prosperity to be maintained with a decreasing GDP.

4. Conclusions

This paper has studied decoupling and dematerialization in the EU-15 in the period 1970–2018 through Ecological Elasticity. The data used are obtained through Material Flow Analysis, using both territorial and consumption approaches, which allows us to test the differences between the two. The main conclusions are:

In general, through Domestic Material Consumption a higher degree of decoupling is achieved, and many countries reach dematerialization, including the EU-15 average. In contrast, using the Material Footprint, although decoupling is generally achieved, dematerialization is exceptional. In fact, using Ecological Elasticity, only Germany achieves dematerialization in the period 1970–2018.

The difference between these indicators is explained by the fact that they do not actually measure the same thing. The Domestic Material Consumption can measure environmental consumption that occurs within one's own territory and is therefore a good approximation of local environmental impact. However, in a global economic system in

which trade is so important, the most appropriate way of knowing the real physical needs of a country is to analyze the material consumption associated with its final demand. This data is obtained through the Material Footprint, so that, through the difference between both indicators, known as Indirect Trade Flows, it is possible to determine the environmental burden that each country transfers to or receives from the rest of the world. In the case of the EU-15 countries, they have positive Indirect Trade Flows, i.e., they all depend on material consumption in other countries to complete the material consumption required for their final demand.

The analysis of the results also allows us to check the advantages and disadvantages of each indicator. In the case of Decoupling Factor and Decoupling Ratio, the main problem is that it does not provide information on the type of decoupling, so it is not possible to identify whether dematerialization exists. As regards the Tapio Decoupling Index, it is not a suitable indicator for very long-time intervals, since it omits the intermediate periods and, therefore, does not reflect the variability of these. On the other hand, it is useful for assessing decoupling on a year-on-year basis, especially by applying Tapio's assessment criteria in Table 1. Ecological Elasticity, on the other hand, has the advantage of capturing the variability of all the periods contained in the interval analyzed, thus providing a much more complete measure of decoupling. It also allows us to distinguish between different types of decoupling, including dematerialization, although its usefulness diminishes when used to study short time periods.

Therefore, through this research it can be concluded that Ecological Elasticity is a simple but useful indicator to study the relationship between economic growth and material consumption over long periods of time. To analyze the inter-annual evolution, it can be completed with Tapio Decoupling Index. On the other hand, it is important to properly select the method by which the data used to calculate the decoupling indicators are obtained, as the conclusions they lead to can be very different. Thus, to determine the material consumption required by an economy, it is most appropriate to use the consumption method, whose indicator is the Material Footprint.

CRediT authorship contribution statement

Rosa María Regueiro-Ferreira: Conceptualization, Validation, Resources, Writing – review & editing, Supervision, Project administration, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft. **Pablo Alonso-Fernández:** Conceptualization, Validation, Resources, Writing – review & editing, Supervision, Project administration, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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