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The influence of the Great Recession on the relationship between ecological footprint, renewable energy and economic growth

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ABSTRACT

This paper studies the relationship between ecological footprint, economic growth and renewable energy use in 20 OECD countries from 1990 to 2019, paying special attention to the possible existence of structural changes in this relationship over the period studied. Our results provide evidence supporting the presence of breaks, with the Great Recession playing a very important role. Our analysis identified an initial phase of decoupling between economic growth and ecological footprint, which is accompanied by a negative estimation of the semi-elasticity between renewable energy and ecological footprint. Nevertheless, these patterns are becoming less evident after the Great Recession, which has been revealed as a negative factor for the environment. Our results alert us to the need to maintain the environment policies even in periods of crisis, the only way to guarantee a real transition towards a more sustainable economic growth.

1. Introduction

The world has experienced exponential progress in economic and social growth in recent decades. This has generated very positive outcomes, such as the development of essential infrastructure, poverty alleviation and improvement in people's quality of life. However, it should be noted that this growth came at the cost of significant environmental degradation in both developed and developing nations, as is noted in Ahmed et al. (2021). This lack of balance between cost and benefits clearly questions the appropriateness of this type of growth, leading researchers and policy-makers to analyze the sustainability of this expansionary socioeconomic process.

The major concern is the environmental degradation generated by this unbalanced growth. This degradation is clearly perceptible if we take into account the evolution of some environmental indicators, with the Greenhouse Gases emissions (GHG), and the dioxide carbon emissions (CO2) being the most popular ones. However, we should consider the existence of more comprehensive alternative environment indicators. A particularly interesting one is the so-called ecological footprint. In this regard, we should note that Global Footprint Network describes ecological footprint as a measure of the area of biologically productive land and water an individual, population, or activity requires to produce all the resources it consumes and to absorb the waste it generates, using prevailing technology and resource management practices. The ecological footprint was in equilibrium with Earth biocapacity in 1970. However, 1.75 Earths were required to regenerate the environmental degradation incurred by 2018, showing that humanity has grown at a pace that surpasses the Earth's capacity for regeneration (Özpolat, 2022; WWF Global Footprint NetworkZSL, 2010).

Consequently, it appears crucial to reduce our ecological footprint in order to mitigate the impact of growth on the environment. This requires adopting policies to limit our consumption of natural resources to ensure a sustainable future for humanity, and considering the preservation of our planet as a top political priority for the majority of countries (Charfeddine, 2017; Nasrollahi et al., 2020; Taghvaee et al., 2023). This new vision of the balance between growth and sustainability has led legislators to enact environmental preservation laws. For instance, the European Commission presented its Communication on the European Green Pact on December 11, 2019. This Green Pact sets out a detailed vision for making Europe a carbon-neutral continent by 2050 through the provision of clean, affordable and secure energy. Similarly, the UN General Assembly's adoption of the 2030 Agenda for Sustainable Development is the fundamental agreement, which serves as the cornerstone of environmental policy adoption for the nations involved. This agenda includes several goals which are clearly related to environmental protection such as Goal 6 that focuses on challenges related to water accessibility and water stress, Goal 7 focuses on the imperative shift towards an energy framework founded on renewable energy

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sources, and Goals 12–13 aimed at the reduction of excessive emissions of pollutants. The influence of these laws has been investigated in some recent papers, such as those of Nunez-Rocha and Martínez-Zarzoso (2019) and Nazlioglu et al. (2021), who have noted the effectiveness of these international agreements in improving the environment.

Given the importance of this issue, it comes as no surprise that a growing number of researchers are also dedicating their efforts to analyzing environmental degradation. Most of them use CO2 as the main environmental indicator (Kabir et al., 2021; Mardani et al., 2019; Debone et al., 2021; Gaies et al., 2022). Nevertheless, an increasing number of studies are now embracing the ecological footprint as a key variable for evaluating environmental conditions (Ikram et al., 2021; Hassan et al., 2019; Ekeocha, 2021). According to these authors, the ecological footprint may reflect the effect of economic growth on factors such as land or water use, which are not directly considered by indicators based on the measure of air pollutants.[1]

Within this field of investigation, researchers have consistently explored the ecological footprint in relation to various socioeconomic factors to understand their combined impact on the environment. Commonly analyzed variables include urbanization (Sun et al., 2022), energy consumption (Baz et al., 2020; Kongbuamai et al., 2021), and economic growth (Kihombo et al., 2021; Yilanci et al., 2023). Regarding economic growth, studies focusing on OECD countries reveal a direct relationship with the ecological footprint, although this relationship may be non-linear (Kızılgöl and Öndes, 2022; Hassan et al., 2023; Zhang et al., 2022).

However, the use of factors alternative to the socioeconomic ones could be appropriate. Specifically, we are thinking of incorporating the use of renewable energies as a possible explanatory variable of the environmental indicators. In our view, the substitution of the standard sources of energy by renewable ones might have helped to balance the economic growth/sustainability relationship. In this regard, we should note that most countries have recently initiated a process of replacing traditional energy generation methods, which are generally very harmful to the environment, with alternatives that better utilize natural resources and promote the sustainability of economic growth. This shift towards more sustainable energy sources not only addresses the need to reduce CO2 emissions (Razmjoo et al., 2021; Saidi and Omri, 2020; Pata et al., 2023) but also contributes to a more efficient and responsible management of natural resources (Usman and Balsalobre-Lorente, 2022a). According to the existing literature, this substitution process could have a positive effect on reducing the ecological footprint, thereby supporting a more balanced relationship between environmental sustainability and economic growth.

Most previous studies, including those by Bajan and Mrówczyńska-Kamińska (2020), Sun et al. (2020), and Lenzen et al. (2018), rely on cross-sectional econometric techniques. While these studies provide valuable insights, they lack a time-series perspective, which is essential for capturing dynamic phenomena such as parameter instability. Specifically, we refer to the potential effects of the Great Recession on decision-making regarding the generation of the Ecological Footprint in OECD countries.

Although the impact of the Great Recession on economic growth is well-documented[2], its effects on renewable energy use and the Ecological Footprint are less studied. This economic crisis significantly disrupted investments in renewable energy, slowing the transition to sustainable energy sources. Financial constraints and geopolitical risks further hindered progress (Alsagr and Van Hemmen, 2021), exacerbating environmental challenges as contractions in the economy often increased reliance on less sustainable energy sources, worsening the Ecological Footprint. Similarly, Alcay et al. (2021) observed related effects in their analysis of waste generation. These findings highlight the importance of examining whether the Great Recession led OECD countries toward less sustainable policies, potentially triggering a worrying regression in sustainability.

Against this background, our aim is to examine the relationship between the ecological footprint, economic growth, and the use of renewable energies, with a particular focus on the latter due to its pivotal role in assessing the benefits of adopting more sustainable energy policies.

This study delves into the non-linear interrelationship among the three variables, with special attention given to effect of the Great Recession. The findings are highly significant, offering robust evidence of the advantages of renewable energy adoption. In particular, our results demonstrate its dual capacity to support economic growth and safeguard environmental sustainability, even during periods of economic crises. These insights provide essential guidance for policymakers and researchers, equipping them with the knowledge needed to design more effective and forward-looking environmental and economic policies.

The paper is organized as follows. Section 2 comprises a descriptive analysis of the available data. Section 3 provides an explanation of the methodology employed. The results are presented in Section 4 and a full discussion is undertaken in Section 5. Finally, Section 6 concludes with a summary of the research findings.

2. Data and descriptive analysis

2.1. Data

To analyze the relationship between the ecological footprint, the evolution of the economy and the use of renewable energies, we have selected the following variables. We have employed the per capita ecological footprint (EF) measured in per capita global hectares (gha)[3] from Global Footprint Network. As mentioned earlier, this variable may offer a more complementary perspective on environmental degradation than the variables commonly employed in the literature, such as CO2 and GHG emissions. Following Li et al. (2022), EF encompasses the consumption of natural resources such as minerals, water, forests, and land resources, aspects that may be ignored when environmental degradation is exclusively measured by air pollutant indicators.

To assess economic evolution, we have utilized per capita gross domestic product (GDP)[4] data obtained from the World Bank. Finally, the use of renewable energies (RE) has been calculated as the percentage of usage relative to the total energy consumed, with data sourced from the OECD.

Data for these variables are available for 20 OECD countries covering the period from 1990 to 2019. The sample size is constrained by data availability, as complete information is not accessible prior to 1990 for the selected countries. Additionally, data beyond 2019 is significantly influenced by the effects of the COVID-19 pandemic.

The countries we have selected are Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom and United States of America. Table 1 presents some descriptive statistics relating to the variables under examination. We have also computed the average growth rate for the entire sample period, the period leading up to the Great Recession (1990–2008), the crisis years (2008–2012), and the subsequent recovery

[1] See Li et al. (2019) in this regard.

[2] See Ng and Wright (2013) and Christiano et al. (2015) in this regard.

[3] The global hectare is a unit of measurement for the ecological footprint of people or activities and the biocapacity of the Earth or its regions. A global hectare can be considered as the world's annual amount of biological production for human use and human waste assimilation, per hectare of biologically productive land and fisheries.

[4] The per capita gross domestic product is based on purchasing power parity (PPP), constant 2017 international dollars.

Table 1
Descriptive analysis.

	Ecological Footprint pc						GDP pc						Renewable Energies (%)					
	1990	2019	g_{9019}	g_{9008}	g_{0812}	g_{1219}	1990	2019	g_{9019}	g_{9008}	g_{0812}	g_{1219}	1990	2019	g_{9019}	g_{9008}	g_{0812}	g_{1219}
Austria	5.31	5.79	0.30%	1.17%	−2.02%	−0.60%	37495	55806	1.38%	1.96%	0.06%	0.66%	25.17%	33.98%	1.04%	0.92%	3.74%	−0.16%
Belgium	7.54	7.22	−0.15%	0.41%	−1.13%	−1.01%	35507	51988	1.32%	1.74%	−0.11%	1.08%	1.27%	10.20%	7.45%	6.51%	18.12%	4.12%
Canada	8.87	7.88	−0.41%	−0.10%	−1.04%	−0.82%	34563	49176	1.22%	1.58%	0.15%	0.92%	22.53%	22.47%	−0.01%	−0.31%	0.16%	0.67%
Denmark	8.71	7.30	−0.61%	−0.54%	−4.45%	1.48%	39028	56814	1.30%	1.71%	−0.84%	1.49%	7.05%	37.29%	5.91%	5.52%	9.78%	4.76%
Finland	7.00	5.20	−1.02%	0.18%	−5.89%	−1.23%	32939	48583	1.35%	2.21%	−1.50%	0.80%	24.51%	45.60%	2.16%	1.94%	2.85%	2.36%
France	6.00	4.85	−0.73%	0.01%	−2.68%	−1.52%	33843	45923	1.06%	1.34%	−0.12%	1.01%	10.54%	15.53%	1.35%	0.03%	3.89%	3.33%
Germany	6.89	4.72	−1.30%	−1.18%	−1.58%	−1.45%	36699	53874	1.33%	1.46%	1.15%	1.11%	2.10%	17.07%	7.49%	9.21%	7.40%	3.26%
Greece	4.72	4.30	−0.32%	1.44%	−7.00%	−0.85%	24263	29722	0.70%	2.43%	−6.71%	0.69%	7.81%	18.52%	3.02%	0.35%	14.24%	3.90%
Ireland	6.49	4.88	−0.98%	−0.40%	−5.37%	0.10%	26782	86926	4.14%	4.23%	−1.28%	7.14%	2.28%	12.33%	5.99%	3.44%	13.28%	8.65%
Italy	5.11	4.20	−0.67%	0.29%	−4.31%	−1.01%	36586	42739	0.54%	1.11%	−1.80%	0.42%	3.78%	17.27%	5.38%	6.02%	7.39%	2.64%
Japan	5.45	4.24	−0.86%	−0.66%	−0.39%	−1.65%	32846	41654	0.82%	0.93%	−0.03%	1.04%	4.34%	7.76%	2.02%	0.13%	1.32%	7.49%
Luxembourg	12.86	12.26	−0.16%	0.97%	−2.17%	−1.89%	70861	114542	1.67%	2.88%	−1.30%	0.30%	1.71%	16.45%	8.12%	4.78%	1.18%	21.74%
Netherlands	6.75	6.36	−0.20%	0.61%	−2.83%	−0.76%	36461	56784	1.54%	2.19%	−0.94%	1.30%	1.18%	8.61%	7.09%	6.93%	5.60%	8.39%
Norway	6.49	5.32	−0.68%	0.38%	−2.90%	−2.09%	42302	64983	1.49%	2.33%	−0.63%	0.58%	59.17%	60.60%	0.08%	−0.07%	−0.33%	0.71%
Portugal	4.14	4.18	0.04%	0.43%	−4.59%	1.74%	23557	34946	1.37%	1.77%	−1.71%	2.13%	26.95%	28.19%	0.16%	−0.83%	2.42%	1.43%
Spain	4.51	4.03	−0.39%	0.88%	−7.60%	0.63%	27543	40782	1.36%	1.99%	−2.29%	1.89%	10.58%	16.68%	1.58%	−0.46%	12.77%	0.82%
Sweden	6.31	5.55	−0.44%	−0.13%	0.11%	−1.56%	34157	52851	1.52%	1.90%	0.18%	1.29%	34.06%	52.87%	1.53%	1.33%	2.82%	1.30%
Switzerland	6.45	3.98	−1.65%	−0.59%	−3.26%	−3.40%	56232	69924	0.75%	0.91%	−0.16%	0.88%	16.80%	24.76%	1.35%	0.85%	2.85%	1.78%
U. Kingdom	5.77	3.87	−1.36%	0.06%	−4.99%	−2.88%	31308	47088	1.42%	1.86%	−0.68%	1.49%	0.65%	11.39%	10.38%	7.53%	14.67%	15.52%
U.S.A.	9.77	7.78	−0.78%	−0.30%	−3.74%	−0.32%	40451	62471	1.51%	1.77%	0.17%	1.63%	4.18%	10.42%	3.20%	2.78%	6.25%	2.56%
AV	6.76	5.70	−0.62%	0.15%	−3.39%	−1.21%	36671	55379	1.39%	2.04%	−0.86%	1.63%	13.33%	23.40%	3.76%	2.06%	6.79%	4.28%
SD	2.05	2.03	0.49%	0.67%	2.14%	1.52%	10732	18854	0.72%	0.89%	1.39%	1.66%	14.97%	15.23%	3.16%	2.94%	5.49%	5.18%

This table presents the values at the beginning (column 1990) and at the end of the sample (2019). The other columns show the average growth rates for the total sample (g_{9019}), the pre-Great Recession period ($g_{90\text{-}08}$), the initial years of the Great Recession (g_{0812}) and the recovery of the economies (g_{1219}). The sample average (AV) and the standard deviation (SD) of the metrics are presented at the bottom of the table. The variables employed in the paper: per capita Ecological Footprint, per capita Gross Domestic Product and the share of the Renewable Energies over the total Energy.

period (2012–2019). This categorization will facilitate our analysis of whether certain effects associated with the Great Recession exist.

2.2. Descriptive analysis

The statistics presented in Table 1 offer some interesting insights. For instance, the initial EF values in the sample display a range spanning from 12.86 gha in Luxembourg to 4.14 in Portugal, with a standard deviation of 2.05 and an average of 6.76. This range shifts from 12.26 (Luxembourg) to 3.87 (United Kingdom) with a standard deviation of 2.03 and an average of 5.70 by the end of the sample period. We can also observe the distribution of these data in Fig. 1.

The average growth rate of the variable over the entire period is negative in most countries, except for Austria (0.30%) and Portugal (0.04%). Switzerland (−1.65%), the United Kingdom (−1.36%), Germany (−1.30%), and Finland (−1.02%) stand out as the countries that achieved the most significant reductions in their EF. However, the behavior of this variable is more heterogeneous when considering the previously mentioned sub-periods.

During the period before the Great Recession (1990–2008), some countries such as Canada (−0.10%), Denmark (−0.54%), Germany (−1.30%), Ireland (−0.98%), Japan (−0.66%), Switzerland (−0.59%), Sweden (−0.13%) and the U.S.A. (−0.30%) managed to reduce their EF. Nevertheless, the rest of the countries experienced an increase in their EF during this period, with Greece (1.44%) and Austria (1.17%) standing out as the countries with the largest increments.

In the years of the Great Recession (2008–2012), the average growth rate of this variable experienced a sharp decline in all countries, except for Sweden, where it increased by 0.11%. This period exhibits a remarkable reduction in EF (−3.39% on average), highlighting the evident connection between economic evolution and environmental degradation. Countries that showed the most significant reductions in their EF were Spain (−7.60%), Greece (−7.00%), and Finland (−5.89%). However, it is important to note that the data exhibits a high degree of heterogeneity.

The EF behavior remains diverse in the last period considered (2012–2019). Some countries continued to undergo a decrease, albeit with more modest values, with growth rates of around −1.00%. Meanwhile, other countries, such as Denmark (1.48%), Ireland (0.10%), Portugal (1.74%), and Spain (0.63%), did not sustain this decline, and their average growth rate increased during these years of economic recovery. It becomes apparent that in these years of economic recovery, some countries were once again experiencing an upward trend in their EF.

Let us now consider the case of GDP, whose evolution is reflected in Fig. 2. When we analyze the average growth rates from 1990 to 2019, it is evident that all countries experienced positive and extremely similar economic growth, averaging 1.39% with a standard deviation of 0.72%. Notably, Ireland stands out with a remarkable growth rate of 4.14% during these years.

We can observe a similar trend across all countries for the period before the Great Recession (1990–2008), although it exhibits a slightly higher average rate (2.04%) and a greater standard deviation (0.89%). Ireland continued to lead with a growth rate of 4.23%, followed by Luxembourg (2.88%), Greece (2.43%), Norway (2.33%), and Denmark (2.21%).

The behavior of GDP underwent a downward shift during the hardest years of the Great Recession (2008–2012), although Austria (0.06%), Germany (1.15%), and Sweden (0.17%) maintained slightly positive growth rates. However, all other countries experienced a significant decrease in their average growth rates.

Finally, at the end of the period (2012–2019), all countries returned to positive average growth rates, showing a gradual economic recovery. Ireland experienced the most significant increase in its growth rate (7.14%), and Spain, for example, transitioned from a decline of −2.29% to a positive growth rate of 1.89%. While all countries exhibited positive average growth rates, the variation between them is somewhat greater than when considering the whole period.

Lastly, let us examine the data on the use of renewable energy as a percentage of total energy consumption (RE). The evolution of this variable is presented in Table 1 and Fig. 3, where we can see a substantial heterogeneity among the countries at the beginning of the sample. For instance, Norway consumed 59.17% of renewable energy in 1990, while the United Kingdom used only 0.65%. This diversity continued at the end of the period, with Norway maintaining its position as the leader in the use of renewable energies (60.60%), while Japan became the country with the lowest utilization (7.76%).

If we consider the period 1990–2008, we can see that Canada (−0.31%), Norway (−0.07%), Portugal (−0.83%), and Spain (−0.46%) had negative average growth rates, while the rest had positive rates ranging from 0.03% in the case of France to 9.21% in Germany.

By contrast, during the years of the economic crisis (2008–2012), most countries successfully increased their utilization of renewable energy significantly, with Norway being the only exception (−0.33%). These years witnessed the highest average growth rates for this variable in most countries, with many rates exceeding 10%.

In the final years of the period (2012–2019), the average growth rate for RE remained positive for most of the countries, with Austria now being the exception (−0.16%). Nevertheless, it is essential to note that these rates seem to stagnate compared to the growth rates of the previous period. Clear examples of where average growth rates decreased drastically from one sub period to another are Greece (14.24%–3.90%), Italy (7.39%–2.64%), and Spain (12.77%–0.82%).

The descriptive analysis has revealed significant findings. First, there is a clear connection between EF, GDP, and RE. Secondly, this relationship does not appear to be stable over time, exhibiting fluctuations during recessions or periods of growth. However, we should note that these are mere descriptive findings, and should be confirmed by using more advanced econometric tools, such as those presented in the next section.

3. Methodology

Our initial specification relies on the seminal works of Grossman and Krueger (1995) and Holtz-Eakin and Selden (1995) who consider the following linear model:

$$\ln(EF)_{it} = \alpha_i + \beta_{1i}\ln(GDP_{it}) + \beta_{2i}\,ER_{it} + e_{it},\ i = 1, \ldots, 20,\ t = 1990, \ldots, 2019 \quad (1)$$

We should note that this model is a reduced form and, therefore, has the limitation of lacking information on why this relationship exists. However, this is a commonly used specification in the literature given that it has the advantage of summarizing the net effect between the three variables (Grossman and Krueger, 1995).

This model assumes that the parameters remain constant over time, a restrictive assumption considering that certain events could have influenced the relationship between them. The Great Recession serves as a clear example of this. Therefore, it is essential to modify the model to consider the potential presence of structural changes.

We can employ several econometric tools to that end, but we consider that the methodology developed by Bai and Perron (1998, 2003a, 2003b), is the most suitable given its flexibility and good performance even with samples like the one described in this paper. This methodology has the advantage of endogenously determining the number of breaks, as well as the period when these breaks occur. This is based on the estimation of the following model:

$$\ln(EF)_{it} = \alpha_{ij} + \beta_{1ij}\ln(GDP_{it}) + \beta_{2ij}\,ER_{it} + v_{it},\ i = 1, 2, \ldots, 20,\ t = TB_{j-1}, \ldots, TB_j,\ j = 1, \ldots, m+1 \quad (2)$$

where TB_j means the period where the breaks appear, with $TB_o = 1990$ and $TB_{m+1} = 2019$, m being the number of breaks, and v an innovation

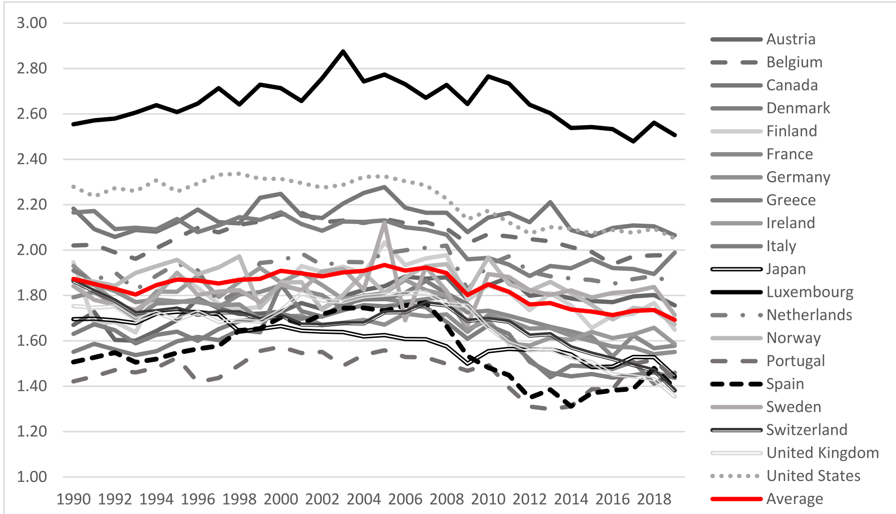


Fig. 1. Evolution of the per capita Ecological Footprint: 1990–2019.

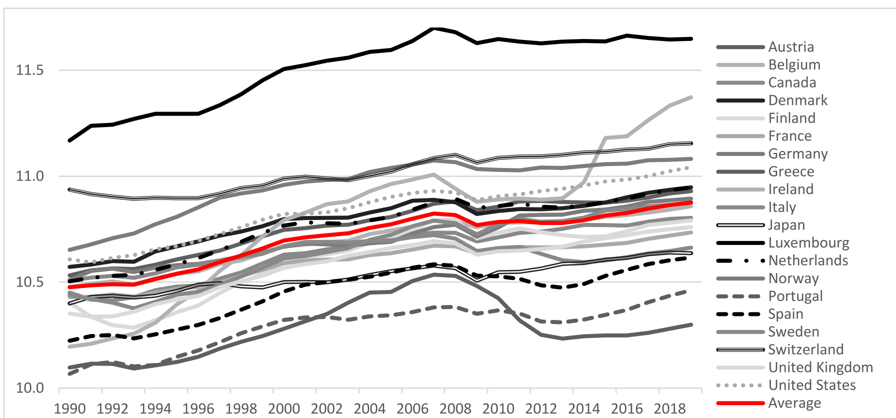


Fig. 2. Evolution of the per capita Growth Domestic Product (in logs):1990–2019.

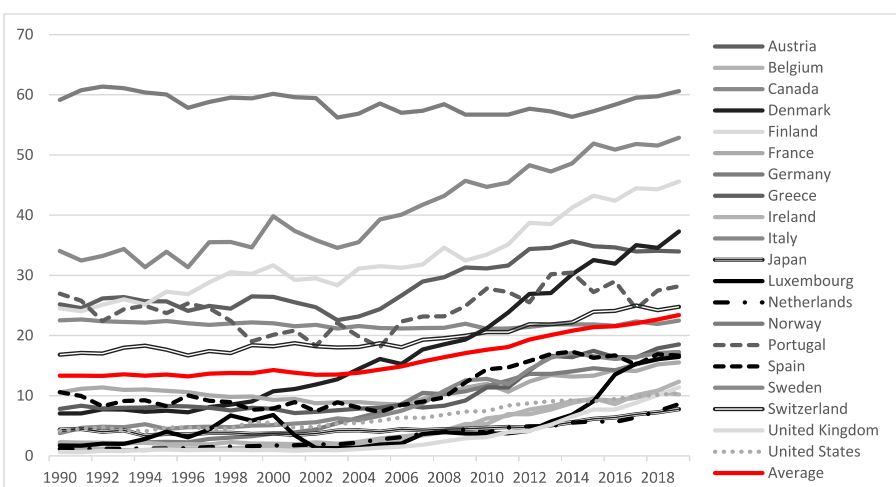


Fig. 3. Evolution of percentage use of Renewable Energies: 1990–2019.

that can follow a wide range of stationary models, including the general ARMA model. Note that the variance of this innovation need not be constant and therefore breaks in the variance are considered as long as they occur on the same dates as the breaks in the regression parameters.

The Bai-Perron (BP) procedure consists of estimating the above equation, considering that the rupture can appear at any point in the sample. We use a Chow-type test to determine the existence of the first rupture. The estimation of the period in which this first break occurs coincides with the period in which the Chow-type statistic minimizes the residuals. The presence of multiple breaks can be analyzed using the UD max and WD max statistics, which test the null hypothesis of no structural breaks against the presence of an unknown number of breaks.

The number of breaks is estimated as a maximum of three breaks. We then apply the sequential procedure defined in Bai and Perron (1998), combined with the partitioning method described in Bai (1997). In those cases where the UD_{max} and WD_{max} reject the non-structural break null hypothesis but the sequential method cannot find any break, we have determined the number of breaks by using the statistics proposed by Schwarz (1978). After this step, we used the quadratic spectral kernel to take into account the presence of possible autocorrelation and heterogeneity in the perturbations, combined with the Andrews (1991) automatic bandwidth selection with an AR(1) approximation.

The Bai-Perron procedure only works properly for non-integrated variables. Therefore, it can only be used in cases where the null hypothesis of unit root has been previously rejected. Therefore, first, we apply the unit root tests. Once we have shown that the variables do not exhibit unit roots, we can apply the BP procedure to estimate the number of breaks and the periods in which these breaks appear.

4. Results

4.1. Unit root inference

Before applying the BP methodology, we should first verify that the considered variables do not exhibit unit roots. The results of the unit root inference are presented in Tables 2–4. The results of these tables are based on a specification that includes an intercept and a trend. We have also considered the possible presence of several breaks in the trend function, to avoid the bias caused by ignoring them.[5] Therefore, we have employed the statistics proposed by Elliott et al. (1996), for the no-break case, and those of Carrion-i-Silvestre et al. (2009), when the breaks in the trend function are present. In this latter case, we have considered a maximum value of 3 breaks.

Our results show that the evidence against the null hypothesis is scarce when no breaks are included in the trend function. However, we can reject it for most of the countries when these breaks are included in the specification. This coincides with the results of, Yilanci et al. (2019) and Churchill et al. (2020) who also consider the presence of breaks when testing for unit roots in environmental variables. We should note that we have also considered the existence of a fourth break for the cases of Austria, Denmark and the Netherlands in order to reject the unit root null hypothesis. We obtained the following values (−5.16, −6.00 and −7.10) in the statistics, respectively.

Once we have checked that the variables are not integrated, we can apply the BP procedure to test for the presence of structural breaks in the relationship between the three variables.

4.2. Estimation of the relationship

Table 5 presents the outcomes of applying the BP methodology to equation (2). The table offers information about the UD_{max} and WD_{max} statistics, which test the null hypothesis of parameter stability, the estimation of the parameters, the corresponding robust standard deviations, and the estimation of the periods when the breaks have occurred.

We can first observe in Table 5 that the WD_{max} and UD_{max} statistics allow us to reject the null hypothesis of structural permanence for most of the countries. The only exception is Sweden. Therefore, the results for this country will be based on the use of the standard ordinary least squares estimation. For the rest of the cases, the relationship between the variables exhibits at least one break, with the presence of two breaks being the most common case. The estimation of the first break is around 1999, possibly related with the generalization of the use of renewable energies. The second break is clearly related to the Great Recession (2007–2013). Therefore, our results confirm our initial suspicions about the existence of a clear impact of the Great Recession on the parameter of our estimated model.

The analysis of the estimated parameters offers very interesting insights. We first focus on the GDP/EF elasticity, which provides useful information in order to study the existence of decoupling between these two variables. Following Wiedenhofer et al. (2020) and Haberl et al. (2020), amongst some others, we should note that GDP and EF are said to be decoupled whenever the elasticity between these two variables is lower than 1 ($\beta_1 < 1$).

The results of Table 5 show that most countries can offer evidence of decoupling, in that the estimation of the parameter β_1 is lower than 1 throughout the entire period. This evidence is particularly strong for Belgium, Canada, Denmark, Germany, Greece, Ireland, Italy, Luxembourg, Spain and the United Kingdom. The rest of the countries exhibit a GDP/EF elasticity greater than 1 for some of the estimated subperiods.

If we consider the last estimated period, mostly related to the post Great Recession period, we can see that the GDP/EF elasticity is greater than 1 for France, Portugal, Japan, the Netherlands and Norway, whilst Austria, Finland, Switzerland and the U.S.A. show an estimated elasticity lower than 1.

Similarly, we can analyze the effect of the Great Recession on decoupling by comparing the GDP/EF elasticities for the pre- and post-Great Recession period. We can observe in Figs. 4 and 5 that some countries transitioned from being decoupled ($\beta_1 < 1$) to not being decoupled ($\beta_1 > 1$) after the impact of this crisis. These countries are France, Japan, Norway and Portugal. Additionally, other countries experienced an increment in this elasticity, namely Denmark, Greece, and Spain. However, the two variables were not decoupled. By contrast, we cannot observe any effect of the Great Recession for Finland and Sweden. The rest of the countries, Austria, Belgium, Canada, Germany, Ireland, Italy, Luxembourg, the Netherlands, Switzerland, United Kingdom and the United States, reduced their GDP/EF elasticities after the Great Recession.

If we now turn our attention to the estimation of the RE/EF semi-elasticity (β_2), Table 5 offers additional interesting insights. First, we should note that the estimation of this parameter is mostly negative, as expected. It is true that we can observe some positive estimated semi-elasticities (Belgium and Greece), but these are clear exceptions, the general rule being a negative or, at least, non-significant semi-elasticity. This confirms our initial intuition that the use of renewable energies may play a relevant role in reducing environmental degradation.

However, our results also show an unexpected effect at the end of the sample. If we compare the estimated RE/EF semi-elasticities for the periods before and after the Great Recession (Fig. 6), we can see that those of Belgium, Germany, Luxembourg, Portugal, Switzerland, the United Kingdom, and the United States of America increase. It is true that this increment is very small in most cases. However, we should also note that only 8 countries show a reduction in the estimated semi-elasticity (Austria, Canada, France, Greece, Italy, Japan, Norway, and Spain). This is a somewhat worrisome situation given that it would be desirable that the substitution of renewable energies could produce a greater reduction in environmental degradation. In any event, we should also note that most of these semi-elasticities are negative at the end of the sample period and, therefore, the effect of RE on EF is still relevant.

5. Discussion

If we take a global view of the results, we can first observe the existence of a noteworthy GDP/EF decoupling process for most countries, as can also be deduced from Ozcan et al. (2020), York et al. (2004), and Szigeti et al. (2017). For instance, the GDP/EF estimated elasticity is

[5] See Perron (1989) and Montañés and Reyes (1998) in this regard.

Table 2
Testing for unit roots: Ecological Footprint per capita.

	ADF-GLS	CKP1	TB1	CKP2	TB1	TB2	CKP3	TB1	TB2	TB3
Austria	−2.20[a]	−3.97[a]	2008	−3.83[a]	2008	2011	−5.41[a]	1993	1996	2008
Belgium	−1.29	−3.86[a]	1999	−4.37[a]	1993	2001	−4.87[a]	1993	2001	2015
Canada	−1.61	−4.37[a]	1998	−5.18[a]	1992	2005	−5.93[a]	1992	2000	2005
Denmark	−2.27[a]	−4.24[a]	2008	−5.54[a]	1997	2008	−5.81[a]	1997	2008	2012
Finland	−2.11[a]	−3.61[a]	2008	−4.87[a]	1993	2008	−6.81[a]	1993	1999	2008
France	−1.37	−3.61[a]	2008	−3.36	1993	2008	−3.27	1993	2008	2016
Germany	−1.76[b]	−2.03	1993	−6.30[a]	1993	2005	−6.24[a]	1993	2005	2009
Greece	−1.42	−2.10	1999	−3.95[a]	1999	2009	−4.98[a]	1999	2006	2013
Ireland	−2.44[a]	−4.06[a]	2008	−4.85[a]	1993	2008	−6.19[a]	1993	2001	2008
Italy	−1.27	−3.11[b]	2007	−4.00[a]	2007	2011	−5.44[a]	1996	2007	2011
Japan	−3.52[a]	−4.30[a]	1997	−4.26[a]	1997	2016	−4.72[a]	1997	2007	2009
Luxembourg	−1.48	−5.51[a]	2002	−3.47	2000	2003	−4.06[a]	2000	2003	2011
Netherlands	−1.88[b]	−4.09[a]	2008	−4.84[a]	1998	2008	−5.25[a]	1998	2008	2011
Norway	−1.55	−2.43	2009	−6.73[a]	1998	2010	−5.89[a]	1998	2008	2010
Portugal	−2.14[a]	−3.36[a]	2010	−5.16[a]	1998	2011	−4.69[a]	1995	1999	2011
Spain	−1.22	−1.96	2007	−4.65[a]	2007	2012	−6.81[a]	1997	2007	2011
Sweden	−2.12[a]	−1.94	2005	−5.40[a]	2004	2006	−5.00[a]	2004	2006	2009
Switzerland	−1.17	−1.49	2006	−4.38[a]	1993	2006	−6.12[a]	1993	2004	2007
U. K.	−0.80	−3.00	2009	−5.12[a]	2000	2009	−5.21[a]	1999	2001	2009
U.S.A.	−1.70[b]	−3.55[a]	2008	−4.25[a]	2006	2009	−4.53[a]	2006	2009	2012

ADF-GLS is the statistic proposed by Elliott et al. (1996) when the specification includes an intercept and a deterministic trend. CKPi is the ADF type statistic proposed by Carrion-i-Silvestre et al. (2009) when the specification includes i breaks that affect both the intercept and the deterministic trend, with i = 1,2,3.
[a] Rejection of the unit root null hypothesis for a 5% significance level.
[b] Rejection of the unit root null hypothesis for a 10% significance level.

Table 3
Testing for unit roots: Gross Domestic Product per capita.

	ADF-GLS	CKP1	TB1	CKP2	TB1	TB2	CKP3	TB1	TB2	TB3
Austria	−1.29	−2.51	2008	−2.46	2008	2011	−2.95	1992	2008	2012
Belgium	−1.31	−2.97	2008	−3.62[b]	1992	2008	−4.39[a]	1992	2007	2010
Canada	−1.35	−3.25[b]	2008	−4.87[a]	1998	2008	−5.48[a]	1997	2006	2009
Denmark	−1.43	−2.66	2008	−3.50	2001	2008	−3.33	2001	2005	2008
Finland	−1.27	−3.24[b]	2008	−3.75[a]	2008	2011	−3.43	1992	2008	2015
France	−1.34	−2.37	2008	−3.43	1997	2008	−4.39[a]	1997	2008	2016
Germany	−1.22	−2.97	2008	−3.62[a]	2002	2008	−4.04[b]	1992	2002	2008
Greece	−2.47[a]	−2.11	2010	−2.10	2005	2010	−4.67[a]	1995	2007	2012
Ireland	−1.02	−1.21	2014	−3.20	2007	2014	−4.92[a]	1997	2007	2014
Italy	−1.16	−1.93	2008	−3.00	2007	2012	−5.17[a]	1999	2007	2013
Japan	−3.02[a]	−3.59[a]	2008	−4.22[a]	1997	2008	−4.74[a]	1995	1999	2008
Luxembourg	−0.83	−2.98	2008	−5.37[a]	1998	2008	−4.90[a]	1998	2007	2012
Netherlands	−1.24	−1.88	2008	−2.18	2001	2008	−3.47	2001	2006	2013
Norway	−0.89	−2.10	2008	−4.88[a]	1996	2008	−2.78	1995	2001	2008
Portugal	−1.28	−1.64	2008	−3.61[a]	1998	2011	−4.12[b]	1992	2000	2011
Spain	−1.31	−1.80	2008	−2.46	2007	2013	−4.13[b]	1997	2007	2013
Sweden	−2.62[a]	−3.08	2008	−5.26***	1993	2007	−5.44[a]	1993	2007	2010
Switzerland	−3.45[a]	−2.60	1992	−3.08	2003	2008	−4.82[a]	1994	2001	2008
U. K.	−1.16	−2.92	2008	−3.98[a]	1996	2008	−4.97[a]	1996	2006	2009
U.S.A.	−1.40	−2.96	2008	−4.55[a]	1997	2008	−4.26[a]	1994	2000	2008

ADF-GLS is the statistic proposed by Elliott et al. (1996) when the specification includes an intercept and a deterministic trend. CKPi is the ADF type statistic proposed by Carrion-i-Silvestre et al. (2009) when the specification includes i breaks that affect both the intercept and the deterministic trend, with i = 1,2,3.
[a] Rejection of the unit root null hypothesis for a 5% significance level.
[b] Rejection of the unit root null hypothesis for a 10% significance level.

greater than 1 only for France, Japan and Norway. The inclusion of some structural breaks has allowed us to find the relevance of the Great Recession in altering this decoupling process. In such a way, we have seen that the GDP/EF estimated elasticities has risen since the Great Recession in Denmark, France, Greece, Japan, Norway, Portugal and Spain. This involves taking steps in the opposite direction of what is recommended for achieving more sustainable economies.

The results regarding the relationship between RE and EF are also aligned with the previous literature, where a negative relationship between these variables has mostly been found. We should cite the works of Saint Akadiri et al. (2019), Sarkodie et al. (2020), Usman et al. (2020), Adekoya et al. (2022) and Ulucak and Khan (2020) in this regard. According to these authors, renewable energies, such as wind, photovoltaic and biofuels, are highly effective in achieving a cleaner environment.

However, our results alert us to the effect that the Great Recession has had on attaining a more sustainable economic growth. More specifically, we have seen that the evolution of the estimated RE/EF semi-elasticity after the Great Recession is quite heterogeneous and, even more importantly, shows that some countries have experienced an increment in the estimation of this parameter. We should note that some authors attribute this effect to a reduction in the use of renewable energies, with a shift towards other forms of energy.[6]

The overall effect of the Great Recession can be considered negative, in the sense that it has led to a halt in the progress towards a more sustainable economic growth. This is evidenced by the fact that only

[6] See Sadiq and Wen (2022) and Usman et al. (2022) in this regard.

Table 4
Testing for unit roots: Renewable Energy.

	ADF-GLS	CKP1	TB1	CKP2	TB1	TB2	CKP3	TB1	TB2	TB3
Austria	−1.52	−2.50	2005	−3.84[a]	2002	2011	−4.05[a]	1998	2002	2014
Belgium	−1.26	−1.85	2003	−4.35[a]	2004	2013	−5.12[a]	2003	2009	2015
Canada	−1.32	−1.53	2002	−7.17[a]	2007	2009	−6.83[a]	2002	2008	2010
Denmark	−0.99	−2.30	2002	−7.44[a]	1998	2010	−8.49[a]	1997	2008	2015
Finland	−1.27	−4.45[a]	2011	−6.86[a]	2000	2011	−6.61[a]	2000	2008	2015
France	−0.85	−5.42[a]	2006	−4.70[a]	2005	2010	−2.41	2005	2010	2013
Germany	−1.56	−2.58	2002	−3.43	2001	2006	−3.83[b]	2001	2006	2015
Greece	−1.00	−2.98	2009	−4.87[a]	2008	2012	−3.92[a]	2008	2010	2013
Ireland	−0.67	−5.81[a]	2004	−3.66[b]	2004	2015	−5.85[a]	2003	2010	2015
Italy	−1.39	−2.78	2007	−4.42[a]	2004	2014	−4.36[a]	2004	2010	2013
Japan	−0.75	−2.92	2012	−4.80[a]	1993	2011	−6.57[a]	1993	2002	2011
Luxembourg	−0.60	−2.32	2012	−3.91[a]	2000	2012	−4.31[a]	2000	2011	2015
Netherlands	−0.52	−2.06	2003	−6.00[a]	2004	2015	−5.53[a]	2003	2009	2015
Norway	−2.01[a]	−3.02	2002	−4.35[a]	2002	2013	−4.80[a]	1995	2002	2013
Portugal	−1.13	−4.32[a]	2005	−5.08[a]	2005	2016	−4.68[a]	2002	2005	2016
Spain	−1.70[b]	−2.62	2008	−6.15[a]	2004	2012	−6.48[a]	1992	2004	2012
Sweden	−2.97[a]	−5.01[a]	2004	−6.10[a]	1999	2004	−6.11[a]	1996	1999	2004
Switzerland	−1.24	−4.57[a]	2005	−5.14[a]	2006	2014	−6.47[a]	1994	2005	2014
U. K.	−0.29	−2.75	2008	−4.45[a]	2005	2011	−4.35[a]	2005	2011	2015
U.S.A.	−1.35	−4.11[a]	2000	−3.98[a]	1998	2000	−5.64[a]	1998	2000	2010

ADF-GLS is the statistic proposed by Elliott et al. (1996) when the specification includes an intercept and a deterministic trend. CKPi is the ADF type statistic proposed by Carrion-i-Silvestre et al. (2009) when the specification includes i breaks that affect both the intercept and the deterministic trend, with i = 1,2,3.

[a] Rejection of the unit root null hypothesis for a 5% significance level.

[b] Rejection of the unit root null hypothesis for a 10% significance level.

Austria, Canada, Italy and, to a lesser extent UK show an evolution of parameter estimates in line with this transition to sustainability (decrease in both GDP/EF elasticity and RE/EF semi-elasticity). In contrast to these countries, Denmark and Portugal show an increase in dependence on GDP, although the RE/EF semi-elasticity remains at similar levels.

Our findings have significant implications for environmental policies in OECD countries, in particular, so far as the effect of crisis on the transition to more sustainable economic growth is concerned. It is crucial for environmental policymakers to recognize the serious deviations that some events, like the Great Recession, caused on the evolution towards sustainability. The re-coupling of economic growth and the related increase in environmental degradation observed in some countries alert us to the need for targeted policy interventions to align economic activities with sustainable environmental practices.

Furthermore, the setback in sustainability progress during the recovery years indicates the necessity for policymakers to reassess and address environmental policies, which should continue even under adverse economic situations. The individualized nature of these deviations suggests the need for tailored environmental policies that account for the specific circumstances and challenges faced by each country. A standardized approach may prove insufficient in effectively addressing the diverse patterns of behavior identified.

In summary, our results show the importance of addressing potential post-crisis deviations, and refining environmental policies to ensure their effectiveness in promoting sustainability.

6. Conclusions

This paper analyzes the relationship between the ecological footprint, economic growth, and the utilization of renewable energy in 20 OECD countries from 1990 to 2019. Our findings show the relevance of considering the presence of structural breaks in this relationship, the impact of the Great Recession being particularly important.

Beyond identifying structural breaks, our analysis reveals that most countries achieved a decoupling between GDP and EF before the economic crisis. However, during the post-crisis recovery years, there is evidence indicating a resurgence of the coupling between economic growth and environmental degradation in certain countries. This insight is very important, highlighting how some nations are recovering economically at the expense of exacerbating environmental degradation.

Our results also show the general negative link between the use of renewable energy and ecological footprint, aligning with our expectations that renewable energy usage contributes to ecological footprint reduction. However, akin to per capita Gross Domestic Product, the later years in the study period witness certain countries diminishing the relationship between these variables.

These findings have substantial implications. Policies geared towards promoting renewable energy usage could potentially foster more environmentally friendly production models (Kazemzadeh et al., 2023; Mrabet et al., 2021). It becomes imperative for OECD countries to redirect their efforts, prioritizing objectives aimed at sustaining economically viable growth with environmental sustainability. For example, studies by Xue et al. (2021) stress the crucial role of robust institutional quality in fostering renewable energy adoption and diminishing reliance on non-renewable sources. Similarly, Raza et al. (2023) highlight positive outcomes in reducing ecological footprint through measures that enhance technical innovation in renewable energies.

Crucially, our findings highlight the heterogeneity among the countries analyzed, suggesting that one-size-fits-all policies may not be effective. Policymaking should take into account the specific circumstances of each country. This research underscores the need for public policies tailored to the unique economic contexts and growth dynamics of individual nations. It also advocates for initiatives that promote the adoption of clean energy to reduce ecological footprints. This involves not only advancing the use of renewable energy, as demonstrated by our estimations, but also implementing stricter emissions regulations and managing the consumption of natural resources. Furthermore, governments should prioritize enhancing institutional quality and fostering technological innovation in the renewable energy sector. Even in times of economic crisis, these measures are essential for ensuring a sustainable and resilient transition toward a cleaner future.

Finally, it is important to acknowledge certain limitations of our study. Specifically, we were unable to evaluate the impact of the COVID-19 pandemic on the relationships between our variables due to the lack of sufficient data beyond 2019. Additionally, the ongoing energy crises may have influenced these dynamics, potentially qualifying our findings. Future research would greatly benefit from an expanded dataset

Table 5
Testing for breaks and Bai-Perron methodology.

	UD max	WDmax	β_o	β_1	β_2	TB_1	β_o	β_1	β_2	TB_2	β_o	β_1	β_2	TB_3	β_o	β_1	β_2
Austria	158	158	−2.05[a]	0.52[a]	−0.07[a]	1997	−10.46[a]	1.16[a]	−0.008[a]	2010	11.46[a]	−0.80[a]	−0.02[a]				
			0.89	0.07	0.005		1.39	0.13	0.002		3.93	0.36	0.003				
Belgium	48	72	−5.92[a]	0.74[a]	0.14[a]	1995	−3.57[a]	0.54[a]	−0.04[a]	2009	6.10	−0.36	−0.02[a]				
			2.40	0.23	0.05		0.92	0.08	0.005		4.28	0.40	0.004				
Canada	28	42	−7.12[a]	0.74[a]	0.06	2005	3.77	−0.02	−0.06[a]								
			2.91	0.20	0.04		3.56	0.38	0.02								
Denmark	132	160	1.95	0.02	−0.003	2008	−2.48	0.42	−0.003								
			1.97	0.19	0.004		7.03	0.66	0.004								
Finland	30	31	−27.45[a]	2.75[a]	0.03	1995	−5.23[a]	0.73[a]	−0.02[a]								
			3.02	0.27	0.02		1.31	0.13	0.002								
France	14	15	3.55[a]	−0.14	−0.02[a]	2013	39.29[a]	4.00[a]	−0.12[a]								
			0.83	0.08	0.005		12.64	1.22	0.03								
Germany	62	92	22.32[a]	−1.97[a]	0.07	1998	−7.74[a]	0.89[a]	−0.01[a]	2011	21.40[a]	−1.85[a]	0.01				
			4.61	0.44	0.04		3.12	0.29	0.004		3.95	0.38	0.008				
Greece	370	449	−5.26[a]	0.65[a]	0.03	1999	5.35[a]	−0.46[a]	0.15[a]	2005	−4.61[a]	0.63[a]	−0.02[a]				
			1.10	0.09	0.03		0.67	0.06	0.02		1.41	0.13	0.004				
Ireland	34	34	−0.17	0.17[a]	0.12	2001	−2.84[a]	0.43[a]	−0.04[a]								
			0.82	0.06	0.11		0.78	0.07	0.004								
Italy	107	107	−3.91[a]	0.53[a]	−0.01	2002	−8.59[a]	0.98[a]	−0.01[a]	2010	1.28	0.05	−0.02[a]				
			1.55	0.15	0.01		2.01	0.19	0.002		1.77	0.16	0.005				
Japan	286	423	−0.17	0.19[a]	−0.03[a]	1997	4.60[a]	−0.27[a]	−0.02[a]	2006	10.70[a]	1.18[a]	−0.06[a]				
			0.80	0.08	0.01		1.15	0.11	0.01		1.92	0.18	0.005				
Luxembourg	93	113	−4.60[a]	0.64[a]	−0.005	2000	0.16	0.23	−0.04[a]	2013	12.08	−0.82	−0.001				
			2.16	0.19	0.01		3.06	0.26	0.007		21.87	1.89	0.004				
Netherlands	84	84	5.70	−0.45	0.72	1996	−14.86[a]	1.57[a]	−0.06[a]								
			6.15	0.64	0.60		1.24	0.11	0.006								
Norway	88	107	−2.84	0.40[a]	0.007	1998	−8.68[a]	0.96[a]	−0.001	2013	106.61	10.40[a]	−0.11[a]				
			1.62	0.10	0.01		4.11	0.33	0.01		218.27	1.74	0.01				
Portugal	31	43	0.23	0.15[a]	−0.01[a]	2010	−9.91[a]	1.13[a]	−0.01								
			0.63	0.06	0.002		3.68	0.34	0.006								
Spain	414	638	−5.26[a]	0.67[a]	−0.007	2001	−1.64[a]	0.31[a]	0.01[a]	2007	−3.16	0.49[a]	−0.03[a]				
			0.80	0.04	0.006		0.44	0.04	0.001		2.14	0.20	0.003				
Sweden	11	13	5.97[a]	0.001[a]	−0.08[a]												
			0.26	0.000	0.02												
Switzerland	83	123	−25.42	2.56[a]	−0.03[a]	1995	−3.18	0.49[a]	−0.03[a]	2011	35.02[a]	−2.99[a]	−0.01[a]				
			3.83	0.34	0.005		2.38	0.23	0.01		7.34	0.67	0.006				
U. Kingdom	187	188	4.23[a]	−0.23[a]	−0.05	1999	−3.69[a]	0.52[a]	−0.02[a]	2009	4.12[a]	−0.23	−0.03				
			0.43	0.04	0.03		1.72	0.16	0.007		13.76	1.30	0.02				
U.S.A.	44	58	−2.95[a]	0.51[a]	−0.04[a]	2000	−15.45[a]	1.68[a]	−0.08[a]	2006	−10.68[a]	1.23[a]	−0.07[a]	2012	8.68[a]	−0.32	0.01
			0.82	0.08	0.01		3.93	0.37	0.02		4.52	0.41	0.007		2.35	0.22	0.01

This table presents UD_{max} and WD_{max} to test the no structural break null hypothesis, which is rejected in all the reported cases when using the appropriate critical values. Robust standard deviations are presented below the estimated parameters. The model is estimated using EF, GDP, and RE, with TBj (i = 1,2,3) representing the estimated periods when the break occurs. The determination of the number of breaks follows the sequential procedure outlined in Bai and Perron (1998).

[a] Means rejection of the non-significance null hypothesis for a 5% significance level.

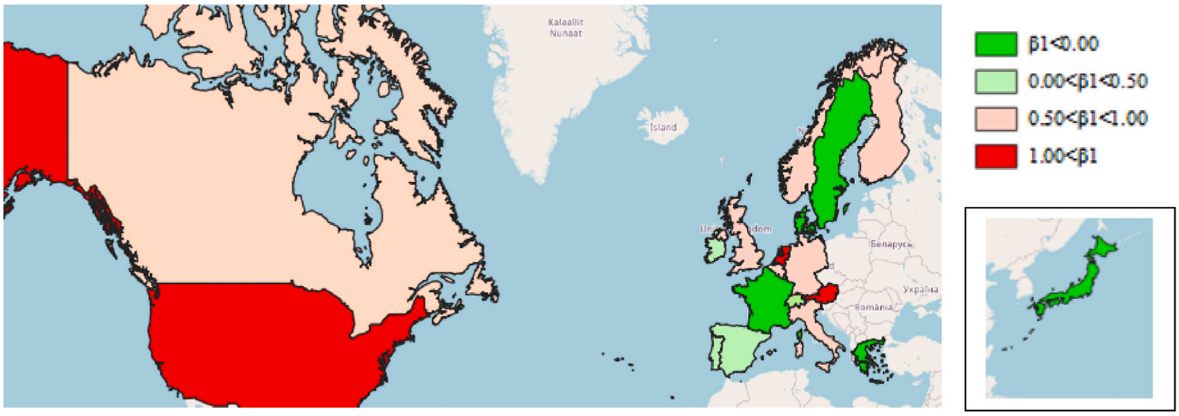


Fig. 4. Estimation of the GDP/EF elasticity. Period before the Great Recession.

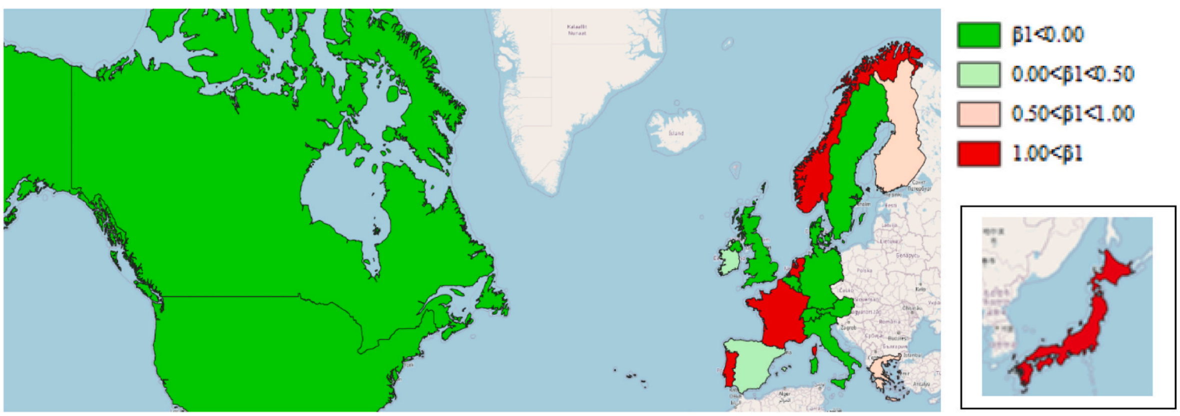
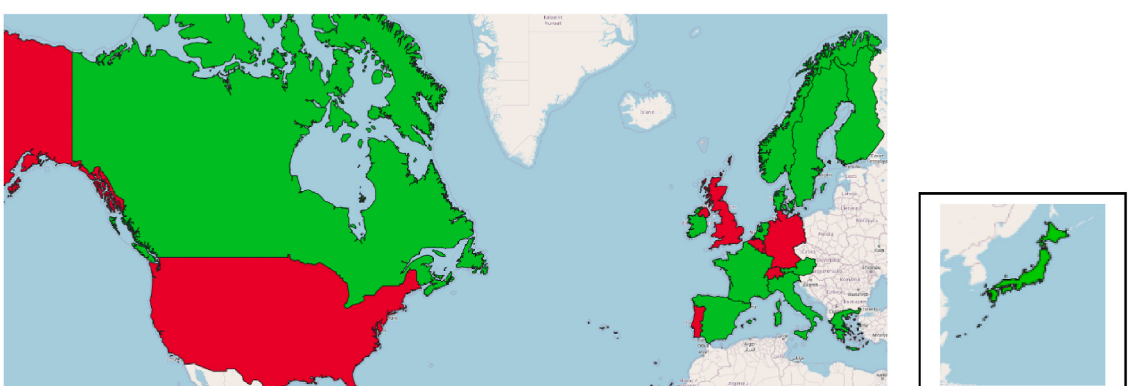


Fig. 5. GDP/EF estimated elasticity. Period after the Great Recession.



$\hat{\beta}_2^{BGR} \geq \hat{\beta}_2^{AGR}$.

$\hat{\beta}_2^{BGR} < \hat{\beta}_2^{AGR}$.

$\hat{\beta}_2^{BGR}$ *and* $\hat{\beta}_2^{AGR}$ represent the estimated RE/EF semi-elasticities for the period before and after the Great Recession, respectively

Fig. 6. Variation of the estimation of the RE/EF semi-elasticity.

that includes post-2019 data, allowing for a more comprehensive analysis.

CRediT authorship contribution statement

Bárbara Baigorri: Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Antonio Montañés:** Writing –

review & editing, Writing – original draft, Supervision, Investigation, Formal analysis. **María-Blanca Simón-Fernández:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition.

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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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Appendix

Table A1
Testing for unit roots: Ecological Footprint per capita

	ADF-GLS	CKP1	TB1	CKP2	TB1	TB2	CKP3	TB1	TB2	TB3
Austria	-2.20**	-3.97**	2008	-3.83**	2008	2011	-5.41**	1993	1996	2008
Belgium	-1.29	-3.86**	1999	-4.37**	1993	2001	-4.87**	1993	2001	2015
Canada	-1.61	-4.37**	1998	-5.18**	1992	2005	-5.93**	1992	2000	2005
Denmark	-2.27**	-4.24**	2008	-5.54**	1997	2008	-5.81**	1997	2008	2012
Finland	-2.11**	-3.61**	2008	-4.87**	1993	2008	-6.81**	1993	1999	2008
France	-1.37	-3.61**	2008	-3.36	1993	2008	-3.27	1993	2008	2016
Germany	-1.76*	-2.03	1993	-6.30**	1993	2005	-6.24**	1993	2005	2009
Greece	-1.42	-2.10	1999	-3.95**	1999	2009	-4.98**	1999	2006	2013
Ireland	-2.44**	-4.06**	2008	-4.85**	1993	2008	-6.19**	1993	2001	2008
Italy	-1.27	-3.11*	2007	-4.00**	2007	2011	-5.44**	1996	2007	2011
Japan	-3.52**	-4.30**	1997	-4.26**	1997	2016	-4.72**	1997	2007	2009
Luxembourg	-1.48	-5.51**	2002	-3.47	2000	2003	-4.06**	2000	2003	2011
Netherlands	-1.88*	-4.09**	2008	-4.84**	1998	2008	-5.25**	1998	2008	2011
Norway	-1.55	-2.43	2009	-6.73**	1998	2010	-5.89**	1998	2008	2010
Portugal	-2.14**	-3.36**	2010	-5.16**	1998	2011	-4.69**	1995	1999	2011
Spain	-1.22	-1.96	2007	-4.65**	2007	2012	-6.81**	1997	2007	2011
Sweden	-2.12**	-1.94	2005	-5.40**	2004	2006	-5.00**	2004	2006	2009
Switzerland	-1.17	-1.49	2006	-4.38**	1993	2006	-6.12**	1993	2004	2007
U. K.	-0.80	-3.00	2009	-5.12**	2000	2009	-5.21**	1999	2001	2009
U.S.A.	-1.70*	-3.55**	2008	-4.25**	2006	2009	-4.53**	2006	2009	2012

ADF-GLS is the statistic proposed by Elliot *et al.* (1996) when the specification includes an intercept and a deterministic trend. CKPi is the ADF type statistic proposed by Carrion-i-Silvestre *et al.* (2009) when the specification includes i breaks that affect both the intercept and the deterministic trend, with i=1,2,3.

** rejection of the unit root null hypothesis for a 5% significance level.

* rejection of the unit root null hypothesis for a 10% significance level.

Table A2
Testing for unit roots: Gross Domestic Product per capita

	ADF-GLS	CKP1	TB1	CKP2	TB1	TB2	CKP3	TB1	TB2	TB3
Austria	-1.29	-2.51	2008	-2.46	2008	2011	-2.95	1992	2008	2012
Belgium	-1.31	-2.97	2008	-3.62*	1992	2008	-4.39**	1992	2007	2010
Canada	-1.35	-3.25*	2008	-4.87**	1998	2008	-5.48**	1997	2006	2009
Denmark	-1.43	-2.66	2008	-3.50	2001	2008	-3.33	2001	2005	2008
Finland	-1.27	-3.24*	2008	-3.75**	2008	2011	-3.43	1992	2008	2015
France	-1.34	-2.37	2008	-3.43	1997	2008	-4.39**	1997	2008	2016
Germany	-1.22	-2.97	2008	-3.62**	2002	2008	-4.04*	1992	2002	2008
Greece	-2.47**	-2.11	2010	-2.10	2005	2010	-4.67**	1995	2007	2012
Ireland	-1.02	-1.21	2014	-3.20	2007	2014	-4.92**	1997	2007	2014
Italy	-1.16	-1.93	2008	-3.00	2007	2012	-5.17**	1999	2007	2013
Japan	-3.02**	-3.59**	2008	-4.22**	1997	2008	-4.74**	1995	1999	2008
Luxembourg	-0.83	-2.98	2008	-5.37**	1998	2008	-4.90**	1998	2007	2012
Netherlands	-1.24	-1.88	2008	-2.18	2001	2008	-3.47	2001	2006	2013
Norway	-0.89	-2.10	2008	-4.88**	1996	2008	-2.78	1995	2001	2008
Portugal	-1.28	-1.64	2008	-3.61**	1998	2011	-4.12*	1992	2000	2011
Spain	-1.31	-1.80	2008	-2.46	2007	2013	-4.13*	1997	2007	2013
Sweden	-2.62**	-3.08	2008	-5.26***	1993	2007	-5.44**	1993	2007	2010
Switzerland	-3.45**	-2.60	1992	-3.08	2003	2008	-4.82**	1994	2001	2008
U. K.	-1.16	-2.92	2008	-3.98**	1996	2008	-4.97**	1996	2006	2009
U.S.A.	-1.40	-2.96	2008	-4.55**	1997	2008	-4.26**	1994	2000	2008

ADF-GLS is the statistic proposed by Elliot *et al.* (1996) when the specification includes an intercept and a deterministic trend. CKPi is the ADF type statistic proposed by Carrion-i-Silvestre *et al.* (2009) when the specification includes i breaks that affect both the intercept and the deterministic trend, with i=1,2,3.

** rejection of the unit root null hypothesis for a 5% significance level.

* rejection of the unit root null hypothesis for a 10% significance level.

Table A3
Testing for unit roots: Renewable Energy

	ADF-GLS	CKP1	TB1	CKP2	TB1	TB2	CKP3	TB1	TB2	TB3
Austria	-1.52	-2.50	2005	-3.84**	2002	2011	-4.05**	1998	2002	2014
Belgium	-1.26	-1.85	2003	-4.35**	2004	2013	-5.12**	2003	2009	2015
Canada	-1.32	-1.53	2002	-7.17**	2007	2009	-6.83**	2002	2008	2010
Denmark	-0.99	-2.30	2002	-7.44**	1998	2010	-8.49**	1997	2008	2015
Finland	-1.27	-4.45**	2011	-6.86**	2000	2011	-6.61**	2000	2008	2015
France	-0.85	-5.42**	2006	-4.70**	2005	2010	-2.41	2005	2010	2013
Germany	-1.56	-2.58	2002	-3.43	2001	2006	-3.83*	2001	2006	2015
Greece	-1.00	-2.98	2009	-4.87**	2008	2012	-3.92**	2008	2010	2013
Ireland	-0.67	-5.81**	2004	-3.66*	2004	2015	-5.85**	2003	2010	2015
Italy	-1.39	-2.78	2007	-4.42**	2004	2014	-4.36**	2004	2010	2013
Japan	-0.75	-2.92	2012	-4.80**	1993	2011	-6.57**	1993	2002	2011
Luxembourg	-0.60	-2.32	2012	-3.91**	2000	2012	-4.31**	2000	2011	2015
Netherlands	-0.52	-2.06	2003	-6.00**	2004	2015	-5.53**	2003	2009	2015
Norway	-2.01**	-3.02	2002	-4.35**	2002	2013	-4.80**	1995	2002	2013
Portugal	-1.13	-4.32**	2005	-5.08**	2005	2016	-4.68**	2002	2005	2016
Spain	-1.70*	-2.62	2008	-6.15**	2004	2012	-6.48**	1992	2004	2012
Sweden	-2.97**	-5.01**	2004	-6.10**	1999	2004	-6.11**	1996	1999	2004
Switzerland	-1.24	-4.57**	2005	-5.14**	2006	2014	-6.47**	1994	2005	2014
U. K.	-0.29	-2.75	2008	-4.45**	2005	2011	-4.35**	2005	2011	2015
U.S.A.	-1.35	-4.11**	2000	-3.98**	1998	2000	-5.64**	1998	2000	2010

ADF-GLS is the statistic proposed by Elliot *et al.* (1996) when the specification includes an intercept and a deterministic trend. CKPi is the ADF type statistic proposed by Carrion-i-Silvestre *et al.* (2009) when the specification includes i breaks that affect both the intercept and the deterministic trend, with i=1,2,3.

** rejection of the unit root null hypothesis for a 5% significance level.

* rejection of the unit root null hypothesis for a 10% significance level.

Data availability

Data will be made available on request.

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