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Black carbon emissions persistence: Evidence from 27 European Union countries using fractional integration

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ABSTRACT

This paper focuses on the analysis of black carbon emissions persistence in the long term (1820–2019) using data for the 27 European Union countries. We extend the traditional analysis based on stationarity I(0) and unit root I(1) tests to the case of fractional integration. Empirical results show very high levels of persistence in the majority of the countries. The hypothesis of mean reversion (i.e., $d < 1$) cannot be rejected in five countries (Denmark, Ireland, Belgium, Malta and Poland) and a slow reverting process is observed. For the rest of the countries, shocks are expected to be persistent with no mean reversion. Structural breaks reveal no major changes in recent times. Therefore, additional policies are recommended to reduce current levels of emissions and to change the long-term pattern.

1. Introduction

Black carbon is a form of particulate matter generated from the combustion of fossil fuels, biofuels, and biomass. In particular, when produced from open burning and controlled combustion it is a range of carbonaceous products of incomplete combustion of biomass and fossil fuel, and is deemed to be one of the major contributors impacting on the global environment and human health [1].It is generally emitted from vehicles, industrial processes, and the burning of wood and other organic materials. Recent studies have identified multiple significant adverse effects of the air pollutant black carbon [2] and their impacts have been analyzed in the past. For instance, Wilkinson et al. [3] examined the effect of hypothetical strategies to improve energy efficiency in UK housing stock to evaluate CO_2 emission savings per million population and year. Ruiz-Mercado et al. [4] studied the adoption and sustained use of improved cooking stoves to improve indoor air pollution or greenhouse gas contributions.

As black carbon is composed of dark and solid particles it absorbs light and heat. Thus, it is a major contributor to global warming due to its ability to produce a greenhouse effect by re-absorbing solar radiation and warming the lower layers of the atmosphere. Moreover, black carbon may impact air quality and human health since inhaling black carbon particles may cause respiratory and cardiovascular diseases and it is responsible for the reduction in air visibility [5].

The first policy undertaken to reduce the impact of black carbon emissions by European Union countries was agreed in Kyoto in 1997. Specifically, the European Community (EC) reached an agreement to target an 8 % decrease in black carbon emissions during the 2008–2012 period in comparison with 1990 levels [6]. Further programmes introduced in the European Union include the European Climate Change Program (ECCP) and the European Emissions Trading Scheme (ETS) [6].

Further programs were introduced in subsequent years to achieve the proposed objectives of reducing gas emissions and increasing renewable energies. After the Paris agreements in 2015, the EC set a more ambitious target by doubling the reduction level up to 40 % (on 1990 levels) and a target of 27 % usage for green energies [7]. In general terms, major

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Table 1
Fractional integration and CO_2 literature review summary.

	Period	Sampling	Countries	Tests	d estimation
Christidou et al. (2013)	1870–2006	Yearly	Global	Unit root testing	
Tiwari et al. (2016)	1960–2009	Yearly	Africa	Unit root testing	unit roots
Erdogan et al. (2022)	0–2014	Yearly	WorldWide	Unit root testing	unit roots
Pata & Aydin [42]	1868–2014	Yearly	G7	Unit root testing	unit roots
Gil-Alana et al. (2017)	1750+ - 2014	Yearly	BRICS	Fractional int	$d > 1$
Gil-Alana et al. (2017)	1750+ - 2014	Yearly	Germany, US, UK	Fractional int	$d < 1$
Gil-Alana and Trani [16]	1960–2013	Yearly	Spain, Italy, Greece and Bulgaria	Fractional int	$d \gg 1$
Gil-Alana and Trani [16]	1960–2013	Yearly	UK	Fractional int	$d < 1$
Gil-Alana and Trani [16]	1960–2013	Yearly	Rest EU	Fractional int	unit root
Gil-Alana & Monge [46]	1880–2015	Yearly	WorldWide	Fractional int	$d = 1.3$
Claudio-Quiroga and Gil-Alana [45]	2019–2020	Daily	G7, EU27 and BRICS	Fractional int	$0.5 < d < 1$
Infante et al. [6]	2000–2022	Monthly	US, JPN, EU5 and BRICS	Fractional int	Brazil, China $d > 1$. Others $d < 1$

Table 2
Values of d and statistical properties.

Value of d	Property
$d < 0$	Anti-persistence
$d = 0$	Short memory or I(0) behaviour
$d > 0$	Long memory or long range dependence
$0 < d < 0.5$	Long memory & Covariance stationary
$0.5 \leq d < 1$	Nonstationary & Mean Reversion
$d = 1$	Unit root process
$d \geq 1$	Lack of mean reversion

European policies in these programs are associated with the increase of the share in renewable and efficient energies; the stimulation of green job creation; the increase in opportunities to recharge or fuel vehicles with alternative fuels; the provision of alternative power supplies for ships and planes; or the introduction of a waste management hierarchy that improves reuse, recycling, recovery, and disposal practices. As a result of all these measures, emissions in Europe have been reduced by 34 % since the agreement (World Bank, WB, 2024).

Most recent techniques to reduce CO_2 emissions are related to the circular economy. For instance, CO_2 has been used as a green solvent in extraction and synthesis, which reduces toxic wastes and energy inputs, creating ecofriendly waste disposal practices [8]. Since conventional processing uses organic solvents for drug recrystallization, synthesis, and extraction [9,10], recent research [11] replaces traditional solvents with carbon dioxide as it may act both as gas (under low pressure) and as liquid (in high-pressure environments). This duality is favouring new applications, by replacing conventional solvents in purification, reactions, separation and particle sizing [12,13]. Another recent carbon application is the improvement in heat transfer properties by the inclusion of carbon particles in conventional fluids [14]. For instance, carbon single-walled nanotubes (C-SWNT) combine very high thermal conductivity (6600 W/m/K) with low density and are able to change the base fluids properties of transport and characteristics of the heat transfer. A review of these emerging trends in the application of carbon-based materials can be seen in Egbedina et al. [15].

Therefore, the objective of this paper is to analyze the effectiveness of these new policies, analyzing the persistence of black emissions in the long term in all EU countries, with the application of recent econometric developments on the CO_2 emissions field. Specifically for this analysis, a yearly dataset of black carbon emissions (totals per country and per capita) for the last 200 years (1820–2019) will be used to evaluate their persistence magnitude with two major aims: first, to extend the traditional analysis implemented in past studies that are premised on dual stationarity I(0) and unit root I(1) tests to the fractional I(d) case; and second, to determine if emissions are expected to be corrected naturally, displaying mean reversion features in the long term.

A novelty in this field is also twofold. First, in the case of specific persistence studies for UE CO_2 emissions [16] the length of the time series is a 60 year sample, while in our case we include a much longer 200 year sample which encompasses the industrial revolution and the CO_2 maximums (between 1900 and 1960). This should help us to identify long-term patterns and improve the persistence analysis. Second, the application of a recent econometric technique based on fractional integration provides a higher degree of flexibility in the dynamic expression of the variables. In particular, it avoids classical binary results (stationarity I(0) or unit root I(1)); and therefore circumvents incorrect unit root outputs in cases when the differencing parameter is close to one ($0.5 < d < 1$) where time series still exhibits mean reversion properties but at a slower pace ([17,18]; etc.). To complement this study and to analyze the effectiveness of the implemented policies, the existence of structural breaks will also be investigated to discover potential trend changes in the series under examination.

2. Literature review

When starting with specific black carbon emissions inventories, the most recent references on a global scale are Klimont et al. [19] *who presented a comprehensive assessment of historical (1990–2010) global anthropogenic particulate matter (PM) emissions including prirnary carbonaceous aerosols as black carbon (BC) and organic carbon (OC). These authors concluded that global emissions had not changed significantly in that period, but that there were significantly different regional trends, with a strong decline in Europe*. Feng et al. [20] *developed different sets of gridded data for historical open burning emissions, historical anthropogenic, and future scenarios to produce consistent data over 1750–2100 on a sectorial basis. Some other recent studies focus on regional data*, however none specifically for Europe. In particular, Chow et al. [21,22] examined data for California and for the whole of the US; Meyer [23] for Switzerland, Nuñez et al. (2014) for Mexico; Imamoglu and Dengiz [24] for the Black Sea; Wang and Zhou [25] for China and India; Zhang et al. [26] for Central China and Karthik et al. [27] for India. Regarding specific black carbon emissions in Europe, most references are only related to optical impacts ([28,29] or [30] among others). Finally, a third group of papers are related to air quality but focused in specific areas such as Zheng et al. [31] for the Pearl River in China; Pauraitė et al. [32] for the Vilnius region in Lithuania; McDonald et al. [33] for the Los Angeles basin; Mouteva el al [34]. for Salt Lake City; Lee et al. [35] for vehicle production in Fontana, CA also in the US; Crimmin et al. [2] for Auckland, Australia; Tyagi et al. [36] for Delhi, India; and Pino-Cortés et al. [37] for several South-American cities including, among others, Santiago de Chile, Buenos Aires, Asuncion and Sao Paulo, and providing thus an interesting sector distribution.

However, throughout this paper, we are not only interested in black carbon emissions, but also in data analysis and its statistical properties. Specifically, for black carbon emissions, very few papers are found [38]; though there are several studies which analyze the time series properties of general CO_2 emissions and their persistence. In particular, Bond et al. [38] presented an emission inventory of primary black carbon and primary organic carbon aerosols (1850–2000) on a worldwide national and sectoral basis, but only modelling these contributions with

Table 3
Descriptive statistics.

	Mean	Median	Max.	Min.	Std. Dev.	Std.Dev/Mean	Skewness	Kurtosis	Jarque-Bera	Probability	Obs.
AUSTRIA	3.15	2.10	9.72	0.69	2.56	0.81	0.65	2.03	29.50	–	270
BELGIUM	11.97	10.96	33.33	1.97	9.34	0.78	0.42	1.77	25.21	3.00E-06	270
BULGARIA	1.90	0.85	9.94	0.42	2.14	1.13	1.89	5.83	250.25	–	270
CROATIA	0.98	0.19	4.40	0.09	1.30	1.33	1.24	2.98	68.86	–	270
CYPRUS	0.21	0.07	1.21	0.03	0.31	1.45	1.98	5.81	265.84	–	270
CZECH_REPUBLIC	6.44	5.30	23.10	2.22	5.04	0.78	1.76	5.42	205.61	–	270
DENMARK	2.22	1.08	7.49	0.35	2.17	0.97	0.83	2.25	37.73	–	270
ESTONIA	0.93	0.27	3.53	0.12	1.13	1.21	1.21	2.87	66.07	–	270
FINLAND	2.71	1.19	10.55	0.29	2.97	1.10	1.16	2.97	61.01	–	270
FRANCE	45.25	47.27	109.98	11.04	27.42	0.61	0.13	1.73	19.00	7.50E-05	270
GERMANY	60.34	44.30	178.18	6.56	52.29	0.87	0.52	1.86	26.93	1.00E-06	270
GREECE	1.55	0.51	8.14	0.24	2.22	1.43	1.91	5.31	223.99	–	270
HUNGARY	5.31	4.96	18.36	1.62	3.26	0.61	1.42	5.23	146.33	–	270
ICELAND	0.12	0.00	0.80	0.00	0.22	1.76	1.57	4.12	124.69	–	270
IRELAND	2.09	1.53	6.25	0.54	1.25	0.60	1.19	3.53	66.76	–	270
ITALY	11.24	5.42	47.35	3.60	11.14	0.99	1.68	4.71	159.56	–	270
LATVIA	1.64	1.52	3.80	0.75	0.81	0.49	0.84	2.87	31.95	–	270
LITHUANIA	1.65	1.25	5.21	0.47	1.23	0.74	1.09	3.57	57.21	–	270
LUXEMBOURG	0.22	0.06	1.12	0.02	0.30	1.36	1.42	3.45	92.89	–	270
MALTA	0.04	0.02	0.29	0.02	0.05	1.17	3.01	12.10	1339.70	–	270
NETHERLANDS	5.32	2.76	23.95	1.00	5.31	1.00	1.18	3.33	63.74	–	270
NORWAY	1.60	0.93	4.72	0.22	1.49	0.93	0.77	2.13	35.28	–	270
POLAND	29.21	25.64	106.30	5.62	23.18	0.79	0.75	2.61	27.25	0.00	270
PORTUGAL	22.94	22.52	41.88	7.07	5.41	0.24	0.74	6.91	197.07	–	270
ROMANIA	6.01	4.79	14.90	1.87	3.49	0.58	0.63	2.16	26.03	0.00	270
SLOVAK_REPUBLIC	1.95	1.42	7.68	0.83	1.54	0.79	2.16	6.91	383.06	–	270
SLOVENIA	0.40	0.07	2.24	0.04	0.66	1.67	1.76	4.42	161.75	–	270
SPAIN	8.39	4.82	45.64	1.03	9.60	1.14	1.71	5.93	228.56	–	270
SWEDEN	3.78	3.31	10.22	0.87	2.77	0.73	0.56	2.09	23.48	0.00	270

time-dependent emissions for pollutant species and country. Ni et al. [1] argued that most studies showed a lack of common methodology for describing the mechanisms related to black carbon formation during combustion processes. Therefore, these authors analyzed the black carbon formation from open burning and controlled combustion (worldwide and China) and compared different samples and measuring processes for open burning and controlled combustions.

Regarding persistence analysis and starting with those based on unit root testing, Christidou et al. [39] evaluated the stationarity of CO_2 emissions per capita in the long term (1870–2006) for 36 countries. It was detected that stationarity of CO_2 emissions per capita is more likely to occur in richer countries. Later, Tiwari et al. [40] analyzed CO_2 emissions per capita for 35 countries in Sub-Saharan Africa (1960–2009) finding empirical evidence of stationarity. Erdogan et al. [41], focused on a longer data span (0 b C. – 2014) but for global emissions with clear evidence of unit root properties and non-mean-reverting behaviour in the long term. Pata and Aydin [42] analyzed the per capita CO_2 emissions (1868–2014) for G7 countries, also finding evidence of unit roots in all countries.

However, some papers have questioned stationarity analysis premised on basic unit root testing. In particular, Hassler and Wolters [17] investigated the features of Dickey-Fuller unit root tests; while Lee and

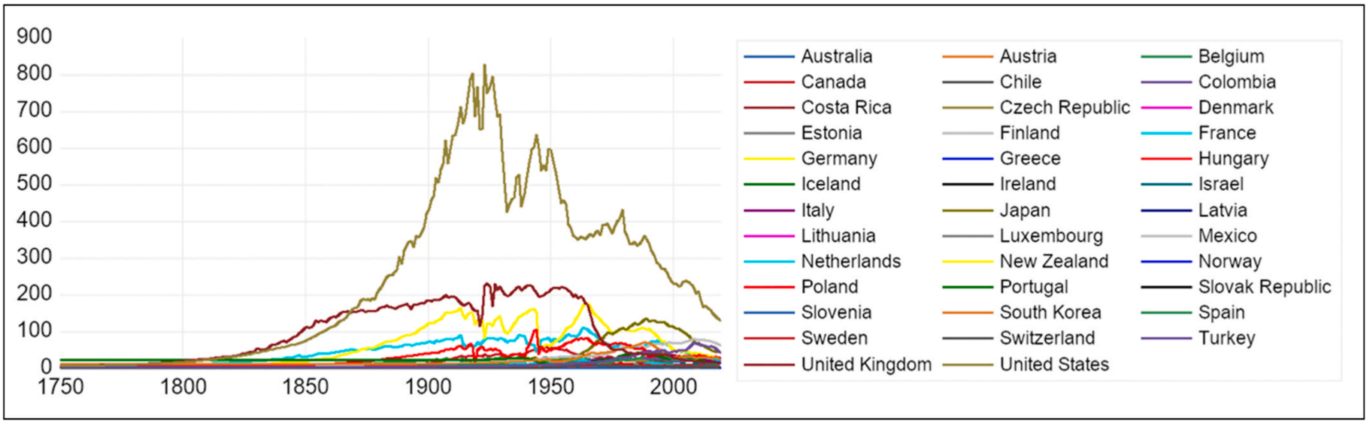

Fig. 1. Visual plot of dataset.

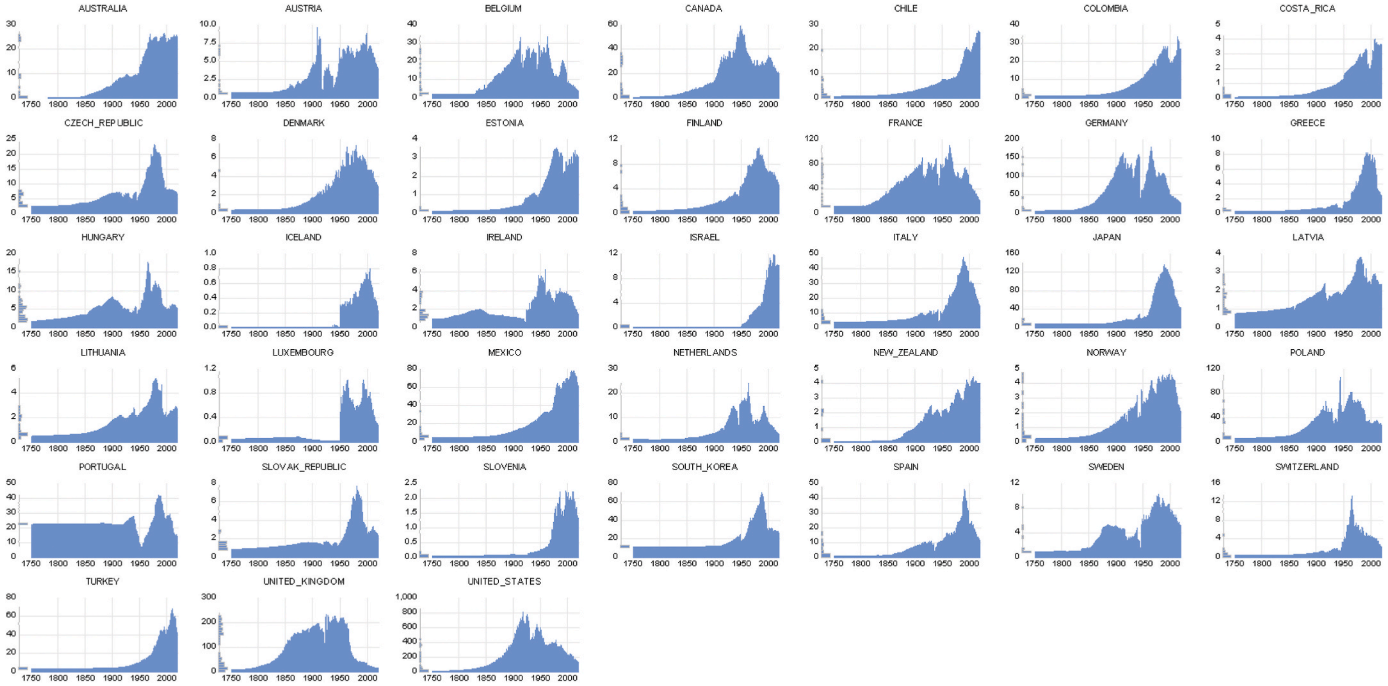

Fig. 2. Visual detail of the dataset per country analyzed.

Schmidt [43] tested KPSS methodologies, finding support for consistency only against clear stationary long memory alternatives, with the integration factor d in the interval (0, 0.5). Caporale and Gil-Alana [18] suggested that some stock series could have unit roots or I(1) but fractionally cointegrated and displaying slow mean reversion properties in the range [0.5, 1). Thus, testing with unit roots methodologies and looking for a binary duality between I(0) and I(1) are restrictive assumptions, as several variables can be long memory nonstationary but mean reverting.

Based on the above, other authors followed stationarity analysis with fractional integration, looking for more precision in the persistence and mean reverting characterization of the time series. Focusing on CO2 emissions, Gil-Alana et al. [44] analyzed the CO_2 emissions for the BRICS and G7 countries for the last 150–250 years, finding empirical confirmation of the significant differences in their persistence features associated with their degree of industrialization. The US, Germany, and the UK display orders of integration in the interval (0.5, 1] with slow transitory effects over these shocks, while the remaining countries have orders of integration equal to or higher than 1 with permanent effects of CO_2 shocks. Gil-Alana and Trani [16] focused on European Union (EU) members, China and the US with shorter spans (1960–2013) with evidence of a significant explosive behaviour ($d > 1$) in European Union countries (Spain, Italy, Greece and Bulgaria), while the UK was the exception with evidence of mean reversion features. However, other studies with higher frequencies and shorter spans show a different behaviour. Claudio-Quiroga & Gil-Alana [45] used daily data with only two years span (within the COVID19 period) for G7, EU27 and BRICS with evidence of mean reversion and values ranging between $0.5 < d < 1$, while Infante et al. [6] used monthly samples in the period (2000–2022) for the largest EU countries, US, Japan and BRICs, finding also evidence of mean reversion in CO_2 emissions, with d values slightly higher than 0.5 in developed countries and above 0.7 in BRICs. Thus, frequency, and especially time span and timing data of the series appear to be key elements which characterize the persistence properties of the CO_2 emissions. Due to the different behaviour of the shorter length studies (data starting after 2000), an interesting issue could be to include an analysis based on structural breaks to confirm policy changes after year 2000 and Kyoto protocol.

Table 4
Estimates of d based on white noise errors.

Country	With no terms	With a constant	With a línear tren
AUSTRIA	**0.97 (0.87, 1.10)**	0.98 (0.88, 1.10)	0.98 (0.88, 1.10)
BELGIUM	**0.94 (0.86, 1.04)**	0.94 (0.87, 1.05)	0.94 (0.87, 1.05)
BULGARIA	1.31 (1.21, 1.44)	**1.32 (1.21, 1.45)**	1.32 (1.21, 1.45)
CYPRUS	**1.27 (1.20, 1.36)**	1.28 (1.21, 1.37)	1.28 (1.21, 1.37)
CZECh REP.	1.24 (1.17, 1.32)	**1.26 (1.19, 1.34)**	1.26 (1.19, 1.34)
GERMANY	**0.99 (0.91, 1.09)**	0.99 (0.91, 1.09)	0.99 (0.91, 1.09)
DENMARK	0.89 (0.82, 0.97)	**0.89 (0.83, 0.97)**	0.89 (0.83, 0.97)
SPAIN	**1.35 (1.26, 1.46)**	1.35 (1.26, 1.47)	1.35 (1.26, 1.47)
ESTONIA	**1.07 (0.98, 1.17)**	1.07 (0.98, 1.18)	1.07 (0.98, 1.18)
FINLAND	1.25 (1.18, 1.34)	**1.26 (1.18, 1.35)**	1.26 (1.19, 1.35)
FRANCE	1.03 (0.95, 1.15)	**1.05 (0.96, 1.16)**	1.05 (0.96, 1.16)
GREECE	**1.31 (1.23, 1.40)**	1.31 (1.23, 1.40)	1.31 (1.23, 1.40)
CROATIA	**0.98 (0.92, 1.05)**	0.98 (0.93, 1.05)	0.98 (0.92, 1.05)
HUNGARY	1.18 (1.09, 1.29)	**1.19 (1.10, 1.30)**	1.19 (1.10, 1.30)
IRELAND	0.84 (0.79, 0.91)	**0.86 (0.80, 0.93)**	0.86 (0.80, 0.93)
ITALY	1.23 (1.16, 1.32)	**1.26 (1.19, 1.35)**	1.26 (1.19, 1.35)
LITHUANIA	1.07 (1.00, 1.16)	**1.08 (1.01, 1.17)**	1.08 (1.01, 1.17)
LUXEMBOURG	**1.23 (1.13, 1.36)**	1.23 (1.13, 1.36)	1.23 (1.13, 1.36)
LATVIA	1.14 (1.05, 1.25)	**1.20 (1.12, 1.31)**	1.20 (1.12, 1.31)
MALTA	**0.87 (0.80, 0.95)**	0.88 (0.81, 0.96)	0.88 (0.81, 0.96)
NETHERLAND	**1.16 (1.06, 1.29)**	1.16 (1.06, 1.29)	1.16 (1.06, 1.29)
POLAND	**0.72 (0.65, 0.82)**	0.73 (0.66, 0.82)	0.73 (0.66, 0.82)
PORTUGAL	1.33 (1.27, 1.41)	**1.34 (1.28, 1.41)**	1.34 (1.28, 1.41)
RUMANIA	0.99 (0.91, 1.09)	**1.01 (0.93, 1.11)**	1.01 (0.93, 1.11)
SLOVAKIA	1.29 (1.21, 1.38)	**1.32 (1.24, 1.42)**	1.32 (1.24, 1.42)
SLOVENIA	**1.03 (0.96, 1.12)**	1.03 (0.96, 1.13)	1.03 (0.96, 1.13)
SWEDEN	1.03 (0.95, 1.14)	**1.04 (0.96, 1.15)**	1.04 (0.96, 1.15)

The values in parenthesis indicate the range of values of do where Ho cannot be rejected at the 95 % level. The values in bold indicate the selected specification for each country.

Table 5
Estimated coefficients with white noise errors.

Country	With no terms	With a constant	With a línear tren
AUSTRIA	0.97 (0.87, 1.10)	–	–
BELGIUM	0.94 (0.86, 1.04)	–	–
BULGARIA	1.32 (1.21, 1.45)	0.414 (1.75)	–
CYPRUS	1.27 (1.20, 1.36)	–	–
CZECH REP.	1.26 (1.19, 1.34)	2.216 (5.03)	–
GERMANY	0.99 (0.91, 1.09)	–	–
DENMARK	0.89 (0.83, 0.97)^{MR}	3.592 (10.80)	–
SPAIN	1.35 (1.26, 1.46)	–	–
ESTONIA	1.07 (0.98, 1.17)	–	–
FINLAND	1.26 (1.18, 1.35)	0.286 (1.86)	–
FRANCE	1.05 (0.96, 1.16)	11.022 (2.81)	–
GREECE	1.31 (1.23, 1.40)	–	–
CROATIA	0.98 (0.92, 1.05)	–	–
HUNGARY	1.19 (1.10, 1.30)	1.614 (3.21)	–
IRELAND	0.86 (0.80, 0.93)^{MR}	0.980 (3.70)	–
ITALY	1.26 (1.19, 1.35)	3.396 (4.26)	–
LITHUANIA	1.08 (1.01, 1.17)	0.468 (3.29)	–
LUXEMBOURG	1.23 (1.13, 1.36)	–	–
LATVIA	1.20 (1.12, 1.31)	0.746 (10.30)	
MALTA	0.87 (0.80, 0.95) ^{MR}	–	–
NETHERLAND	1.16 (1.06, 1.29)	–	–
POLAND	0.72 (0.65, 0.82) ^{MR}	–	–
PORTUGAL	1.34 (1.28, 1.41)	0.197 (1.77)	–
RUMANIA	1.01 (0.93, 1.11)	1.864 (4.32)	–
SLOVAKIA	1.32 (1.24, 1.42)	0.829 (5.95)	–
SLOVENIA	1.03 (0.96, 1.12)	–	–
SWEDEN	1.04 (0.96, 1.15)	0.871 (2.71)	–

The values in column 2 refer to the selected specification for each country. Columns 3 and 4 indicate the estimated coefficients and their corresponding t-values, in parenthesis. Average d of all countries: 1.11.

All these references in terms of the integration factor analysis are summarized in Table 1. It can be seen that most studies have used long and very long span periods with yearly samples, with unit root or d > 1 results in most cases; on the other hand, some recent studies with shorter spans after year 2000 tend to support the hypothesis of mean reversion.

Table 6
Estimates of d based on autocorrelated errors.

Country	With no terms	With a constant	With a línear tren
AUSTRIA	**0.87 (0.70, 1.15)**	0.88 (0.71, 1.15)	0.89 (0.70, 1.15)
BELGIUM	**0.82 (0.73, 0.93)**	0.83 (0.75, 0.94)	0.83 (0.75, 0.94)
BULGARIA	1.16 (1.00, 1.41)	**1.18 (1.00, 1.42)**	1.18 (1.00, 1.42)
CYPRUS	**1.25 (1.13, 1.38)**	1.25 (1.13, 1.39)	1.25 (1.13, 1.39)
CZECH REP.	1.35 (1.23, 1.53)	**1.37 (1.25, 1.55)**	1.37 (1.25, 1.55)
GERMANY	**0.95 (0.82, 1.13)**	0.96 (0.82, 1.13)	0.96 (0.82, 1.13)
DENMARK	**0.94 (0.84, 1.07)**	0.95 (0.86, 1.07)	0.95 (0.85, 1.07)
SPAIN	**1.30 (1.13, 1.56)**	1.31 (1.12, 1.55)	1.31 (1.12, 1.55)
ESTONIA	0.91 (0.83, 1.03)	0.92 (0.83, 1.03)	**0.91 (0.80, 1.03)**
FINLAND	1.21 (1.11, 1.36)	**1.22 (1.12, 1.37)**	1.22 (1.12, 1.37)
FRANCE	0.90 (0.79, 1.05)	**0.93 (0.81, 1.07)**	0.93 (0.81, 1.07)
GREECE	**1.29 (1.17, 1.45)**	1.30 (1.18, 1.46)	1.30 (1.18, 1.46)
CROATIA	**1.10 (1.01, 1.22)**	1.11 (1.01, 1.24)	1.11 (1.01, 1.25)
HUNGARY	1.12 (0.94, 1.34)	**1.11 (0.96, 1.35)**	1.11 (0.96, 1.35)
IRELAND	1.05 (0.93, 1.20)	**1.10 (0.99, 1.25)**	1.10 (0.99, 1.25)
ITALY	1.20 (1.10, 1.35)	**1.23 (1.11, 1.35)**	1.23 (1.11, 1.35)
LITHUANIA	1.15 (1.00, 1.33)	**1.16 (1.01, 1.35)**	1.16 (1.01, 1.35)
LUXEMBOURG	**1.03 (0.89, 1.18)**	1.02 (0.89, 1.19)	1.02 (0.89, 1.19)
LATVIA	1.05 (0.89, 1.25)	**1.16 (0.99, 1.34)**	1.16 (0.99, 1.34)
MALTA	**1.13 (0.95, 1.34)**	1.14 (0.97, 1.35)	1.14 (0.97, 1.35)
NETHERLAND	**0.91 (0.79, 1.08)**	0.93 (0.80, 1.08)	0.93 (0.80, 1.08)
POLAND	**0.71 (0.61, 0.85)**	0.73 (0.63, 0.86)	0.73 (0.63, 0.86)
PORTUGAL	1.59 (1.46, 1.77)	**1.60 (1.47, 1.78)**	1.60 (1.47, 1.78)
RUMANIA	1.00 (0.83, 1.21)	**1.03 (0.88, 1.22)**	1.03 (0.88, 1.22)
SLOVAKIA	1.29 (1.15, 1.45)	**1.31 (1.18, 1.49)**	1.31 (1.18, 1.49)
SLOVENIA	**1.05 (0.93, 1.21)**	1.04 (0.94, 1.22)	1.04 (0.94, 1.22)
SWEDEN	0.90 (0.79, 1.04)	**0.92 (0.82, 1.06)**	0.92 (0.82, 1.06)

The values in parenthesis indicate the range of values of do where Ho cannot be rejected at the 95 % level. The values in bold indicate the selected specification for each country.

Table 7
Estimated coefficients with autocorrelated errors.

Country	With no terms	With a constant	With a línear tren
AUSTRIA	0.87 (0.70, 1.15)	–	–
BELGIUM	0.82 (0.73, 0.93)^{MR}	–	–
BULGARIA	1.18 (1.00, 1.42)	0.414 (1.80)	–
CYPRUS	1.25 (1.13, 1.38)	–	–
CZECH REP.	1.37 (1.25, 1.55)	2.216 (5.24)	–
GERMANY	0.95 (0.82, 1.13)	–	–
DENMARK	0.94 (0.84, 1.07)	–	–
SPAIN	1.30 (1.13, 1.56)	–	–
ESTONIA	0.91 (0.83, 1.03)	0.101 (2.08)	0.011 (2.90)
FINLAND	1.22 (1.12, 1.37)	0.286 (1.74)	–
FRANCE	0.93 (0.81, 1.07)	11.093 (2.85)	–
GREECE	1.29 (1.17, 1.45)	–	–
CROATIA	1.10 (1.01, 1.22)	–	–
HUNGARY	1.11 (0.96, 1.35)	1.615 (3.16)	–
IRELAND	1.10 (0.99, 1.25)	0.970 (3.72)	–
ITALY	1.23 (1.11, 1.35)	3.596 (4.22)	–
LITHUANIA	1.16 (1.01, 1.35)	0.468 (3.34)	–
LUXEMBOURG	1.03 (0.89, 1.18)	–	–
LATVIA	1.16 (0.99, 1.34)	0.746 (10.22)	–
MALTA	1.13 (0.95, 1.34)	–	–
NETHERLAND	0.91 (0.79, 1.08)	–	–
POLAND	0.71 (0.61, 0.85)^{MR}	–	–
PORTUGAL	1.60 (1.47, 1.78)	0.197 (2.01)	–
RUMANIA	1.03 (0.88, 1.22)	1.862 (4.32)	–
SLOVAKIA	1.31 (1.18, 1.49)	0.829 (5.93)	–
SLOVENIA	1.05 (0.93, 1.21)	–	–
SWEDEN	0.92 (0.82, 1.06)	0.881 (2.77)	–

The values in column 2 refer to the selected specification for each country. Columns 3 and 4 indicate the estimated coefficients and their corresponding t-values, in parenthesis. Average d of all countries: 1.10.

3. Methodology

This paper uses fractional integration, which is a singular model that belongs to the category of long memory processes, which are so-named because the high degree of association between observations which are

Table 8
Structural break analysis for black carbon emissions.

	Structural Breaks	d of last period
AUSTRIA	1914, 1955	0.94 (0.67, 1.21)
BELGIUM	1924, 1967	1.40 (1.26, 1.55)
BULGARIA	1976	1.17 (0.80, 1.54)
CYPRUS	1975	1.28 (1.02, 1.54)
CZECH REP.	1976	1.14 (0.94, 1.35)
GERMANY	1925, 1965	1.36 (1.22, 1.51)
DENMARK	1952	0.93 (0.70, 1.17)
SPAIN	1939	1.39 (1.24, 1.53)
ESTONIA	1981	0.90 (0.56, 1.23)
FINLAND	1981	0.91 (0.62, 1.19)
FRANCE	1914, 1955	1.05 (0.98, 1.11)
GREECE	none	1.29 (1.17, 1.45)
CROATIA	1981	0.88 (0.46, 1.31)
HUNGARY	1926, 1965	1.05 (0.68, 1.42)
IRELAND	1921, 1960	0.76 (0.29, 1.22)
ITALY	1949	1.38 (1.25, 1.51)
LITHUANIA	1980	0.94 (0.37, 1.50)
LUXEMBOURG	1950	1.39 (1.29, 1.50)
LATVIA	1981	0.92 (0.65, 1.20)
MALTA	none	0.87 (0.80, 0.95)
NETHERLAND	1964	1.45 (1.35, 1.54)
POLAND	1921, 1960	1.00 (0.81, 1.18)
PORTUGAL	1979	1.23 (0.95, 1.50)
ROMANIA	1980	0.91 (0.56, 1.26)
SLOVAKIA	1981	1.15 (0.99, 1.31)
SLOVENIA	1981	1.00 (0.63, 1.37)
SWEDEN	1946	1.23 (1.06, 1.40)
AVERAGE		1.11 (0.86, 1.35)

far distant in time. Fractional integration is characterized by the number of differences required in a series to render it stationary I(0) or short memory being a non-integer positive value. Thus, a series x(t), t = 1, 2, …is said to be fractionally integrated or integrated of order d if it admits the following representation,

$$(1-L)^{d}\, x(t) = u(t), t = 1, 2 \tag{1}$$

where L is the lag-operator such that $L^k x(t) = x(t-k)$; d is a real positive value, and u(t) is a well-behaved process with mean zero and constant variance and that may include serial correlation as in the stationary AutoRegressive Moving Average (ARMA) processes. Note that if d = 1, we have unit roots, and if u(t) is ARMA(p, q), x(t) follows an integrated ARMA, ARIMA(p, 1, q). The natural generalization of this to any real value d, is the fractional ARIMA (ARFIMA) model of orders p, d, and q, for the AR, the differencing parameter and the MA process respectively. (See Refs. [47–50]) for the representation of these models).

In this context of fractional integration, the differencing parameter (d) plays a crucial role since depending on its value, different modelling assumptions may be established. Thus, for example, long memory takes place as long as d is positive while d = 0 implies short memory behaviour. Covariance (or second order) stationary holds for any d-value below 0.5 while $d \geq 0.5$ implies nonstationarity and the higher the value of d is, the more nonstationary the series becomes. It is nonstationary in the sense that the variance of the partial sum increases with d. On the other hand, mean reversion holds for any value of d below 1, while d implies a lack of this property and permanency of shocks. Table 2 summarizes the features of the model depending on the value of d.

4. Data and results

We retrieved the datasets of black carbon emissions per capita (tons per 1000 persons) of 27 European Union countries for the 1820–2019 period, from Madsen and Ang [51], Feng et al. [20] and the World Bank [52]. Contrary to most of the other providers of black carbon emission data, the datasets used in this paper are not characterized by lack of temporal resolution [20]. The descriptive statistics of black carbon emissions per capita are summarized in Table 3 and visually represented in Figs. 1 and 2 to enhance comprehension of the dataset.

Based on the above data, we implement the following model, that initially incorporates an intercept and a linear time trend, that is,

$$y(t) = \alpha + \beta t + x(t), (1-L)^{d}\, x(t) = u(t), t = 1, 2 \tag{2}$$

where α and β are scalar unknown parameters representing an intercept and a time trend respectively. Using (2), we implement a test of the null hypothesis:

$$H_o : d = d_o, \tag{3}$$

for d_o-values for a range from −1 to 2 with 0.01 increments, collecting only the interval of values where the null cannot be rejected. Moreover, the value producing the lowest statistic can be taken as an estimate of d above since the method employed, and based on Robinson [53] relies on the log-likelihood function.

Across the tables, we report the results for two different scenarios depending on the assumptions made on the error term, i.e., u(t) in (2). Thus, first we suppose that u(t) is a white noise process (i.e., zero mean and uncorrelated with constant variance) and then, weak autocorrelation is permitted by using a non-parametric approximation to an AR process and based on the exponential model of Bloomfield [54]. This is a model that is implicitly described in terms of its spectral density function, which is given by

$$f(\lambda;\ \tau) = \left[\frac{\sigma 2}{2\pi}\right] exp\left[2\sum_{i=0}^{n}\tau_i \cos(\lambda i)\right], \tag{4}$$

where σ^2 is the variance of the error term, and n represents the number of short-run dynamics. According to Bloomfield [54] the log of the above expression is a good approximation for the spectral density of a stationary AutoRegressive (AR) process. Moreover, it produces autocorrelations decaying exponentially as in the AR case and it is stationary across all its values.

For each case, we consider three deterministic set-ups, corresponding to the following cases.

i) without either a constant or a trend, i.e., imposing α = β = 0 in equation (2).
ii) with a constant but without a trend, i.e., with β = 0 a priori in equation (2).
iii) with a constant and a (linear) time trend.

We have marked in bold in the tables the selected specification for each case, which is based on the significance level of these terms in the joint specification of the two equalities in (2). In other words, we jointly estimate α, β and d in equation (2), and if the two coefficients of the deterministic terms (α and β) are significant, we keep that model with the corresponding estimate of d; however, if β is found to be insignificant, we move to a model with an intercept, reporting the new estimate of d along with α; finally, if both, α and β are statistically insignificant, we choose d based on a model with no deterministic terms.

Tables 4and5 refer to the case of white noise errors while those in Tables 6 and 7 allow for serial correlation.

Looking at the results and supposing first that u(t) is uncorrelated, in Tables 4 and 5, the time trend coefficient is found to be statistically insignificant in all cases, while the intercept is required in 15 countries. Looking at the differencing parameter d, we see that there are four countries where the hypothesis of reversion to the mean (d < 1) cannot be rejected. These countries are Poland (with d = 0.72), Ireland (0.86), Malta (0.87) and Denmark (0.89). For the rest of the cases, the unit root null hypothesis cannot be rejected (in nine countries) or it is rejected in favour of d > 1 in the remaining fourteen countries. The highest d corresponds to Spain and Portugal, with the estimates being significantly higher than 1 (1.34 and 1.35 respectively for Portugal and Spain).

Next, we allow for autocorrelation in u(t) (in Tables 6 and 7). In

Table 9
Correlation analysis. Whole sample.

	AUSTRIA	BELGIUM	BULGARIA	CROATIA	CYPRUS	CZECH_REPUBLIC	DENMARK	ESTONIA	FINLAND	FRANCE	GERMANY	GREECE	HUNGARY	ICELAND	IRELAND	ITALY	LATVIA	LITHUANIA	LUXEMBOURG	MALTA	NETHERLANDS	NORWAY	POLAND	PORTUGAL	ROMANIA	SLOVAK_REPUBLIC	SLOVENIA	SPAIN	SWEDEN		AVERAGE
AUSTRIA	1.00	0.66	0.71	0.76	0.72	0.74	0.84	0.76	0.82	0.74	0.69	0.73	0.73	0.74	0.62	0.79	0.87	0.80	0.73	0.61	0.70	0.88	0.76	0.14	0.80	0.67	0.66	0.83	0.88		0.74
BELGIUM	0.66	1.00	0.30	0.23	0.15	0.46	0.58	0.27	0.41	0.96	0.91	0.17	0.61	0.15	0.46	0.29	0.54	0.56	0.27	0.14	0.77	0.55	0.80	-0.10	0.61	0.26	0.04	0.43	0.58		0.45
BULGARIA	0.71	0.30	1.00	0.84	0.76	0.93	0.86	0.92	0.93	0.46	0.48	0.79	0.75	0.81	0.60	0.87	0.89	0.90	0.77	0.70	0.57	0.85	0.63	0.38	0.86	0.94	0.77	0.81	0.85		0.76
CROATIA	0.76	0.23	0.84	1.00	0.92	0.73	0.87	0.96	0.93	0.38	0.32	0.92	0.57	0.96	0.73	0.91	0.85	0.79	0.86	0.75	0.61	0.92	0.54	0.26	0.82	0.78	0.94	0.87	0.82		0.75
CYPRUS	0.72	0.15	0.76	0.92	1.00	0.65	0.75	0.85	0.84	0.30	0.24	0.99	0.45	0.96	0.58	0.95	0.75	0.66	0.82	0.86	0.47	0.85	0.37	0.47	0.70	0.73	0.94	0.92	0.76		0.70
CZECH_REPUBLIC	0.74	0.46	0.93	0.73	0.65	1.00	0.88	0.84	0.92	0.61	0.63	0.70	0.87	0.71	0.60	0.83	0.92	0.95	0.73	0.67	0.63	0.83	0.75	0.40	0.86	0.96	0.66	0.79	0.89		0.76
DENMARK	0.84	0.58	0.86	0.87	0.75	0.88	1.00	0.89	0.96	0.70	0.67	0.77	0.78	0.81	0.81	0.86	0.92	0.93	0.84	0.66	0.85	0.96	0.83	0.19	0.92	0.82	0.72	0.87	0.90		0.81
ESTONIA	0.76	0.27	0.92	0.96	0.85	0.84	0.89	1.00	0.96	0.42	0.41	0.86	0.67	0.90	0.67	0.91	0.91	0.89	0.82	0.74	0.61	0.92	0.61	0.31	0.88	0.88	0.90	0.86	0.86		0.78
FINLAND	0.82	0.41	0.93	0.93	0.84	0.92	0.96	0.96	1.00	0.56	0.54	0.86	0.77	0.89	0.75	0.94	0.94	0.94	0.87	0.77	0.73	0.95	0.71	0.34	0.91	0.92	0.83	0.90	0.91		0.82
FRANCE	0.74	0.96	0.46	0.38	0.30	0.61	0.70	0.42	0.56	1.00	0.91	0.32	0.75	0.32	0.54	0.44	0.67	0.67	0.43	0.25	0.80	0.67	0.84	-0.02	0.71	0.43	0.19	0.54	0.72		0.56
GERMANY	0.69	0.91	0.48	0.32	0.24	0.63	0.67	0.41	0.54	0.91	1.00	0.28	0.75	0.25	0.39	0.42	0.68	0.70	0.34	0.23	0.71	0.62	0.89	0.08	0.71	0.45	0.17	0.51	0.66		0.54
GREECE	0.73	0.17	0.79	0.92	0.99	0.70	0.77	0.86	0.86	0.32	0.28	1.00	0.49	0.96	0.59	0.97	0.78	0.71	0.81	0.88	0.48	0.87	0.40	0.53	0.74	0.77	0.94	0.93	0.78		0.73
HUNGARY	0.73	0.61	0.75	0.57	0.45	0.87	0.78	0.67	0.77	0.75	0.75	0.49	1.00	0.53	0.51	0.62	0.82	0.82	0.65	0.43	0.63	0.72	0.81	0.12	0.75	0.77	0.43	0.61	0.84		0.66
ICELAND	0.74	0.15	0.81	0.96	0.96	0.71	0.81	0.90	0.89	0.32	0.25	0.96	0.53	1.00	0.66	0.93	0.79	0.71	0.91	0.81	0.53	0.87	0.44	0.33	0.72	0.76	0.93	0.89	0.80		0.73
IRELAND	0.62	0.46	0.60	0.73	0.58	0.60	0.81	0.67	0.75	0.54	0.39	0.59	0.51	0.66	1.00	0.64	0.64	0.67	0.74	0.51	0.84	0.77	0.62	-0.02	0.70	0.55	0.52	0.66	0.65		0.62
ITALY	0.79	0.29	0.87	0.91	0.95	0.83	0.86	0.91	0.94	0.44	0.42	0.97	0.62	0.93	0.64	1.00	0.86	0.83	0.84	0.90	0.59	0.91	0.53	0.54	0.83	0.87	0.90	0.97	0.85		0.79
LATVIA	0.87	0.54	0.89	0.85	0.75	0.92	0.92	0.91	0.94	0.67	0.68	0.78	0.82	0.79	0.64	0.86	1.00	0.97	0.74	0.65	0.67	0.93	0.79	0.33	0.93	0.89	0.78	0.85	0.95		0.80
LITHUANIA	0.80	0.56	0.90	0.79	0.66	0.95	0.93	0.89	0.94	0.67	0.70	0.71	0.82	0.71	0.67	0.83	0.97	1.00	0.70	0.64	0.72	0.90	0.82	0.32	0.94	0.90	0.69	0.81	0.90		0.79
LUXEMBOURG	0.73	0.27	0.77	0.86	0.82	0.73	0.84	0.82	0.87	0.43	0.34	0.81	0.65	0.91	0.74	0.84	0.74	0.70	1.00	0.72	0.67	0.82	0.54	0.12	0.67	0.73	0.73	0.82	0.78		0.71
MALTA	0.61	0.14	0.70	0.75	0.86	0.67	0.66	0.74	0.77	0.25	0.23	0.88	0.43	0.81	0.51	0.90	0.65	0.64	0.72	1.00	0.42	0.72	0.31	0.57	0.63	0.74	0.79	0.89	0.67		0.64
NETHERLANDS	0.70	0.77	0.57	0.61	0.47	0.63	0.85	0.61	0.73	0.80	0.71	0.48	0.63	0.53	0.84	0.59	0.67	0.72	0.67	0.42	1.00	0.79	0.80	-0.05	0.78	0.49	0.36	0.67	0.68		0.64
NORWAY	0.88	0.55	0.85	0.92	0.85	0.83	0.96	0.92	0.95	0.67	0.62	0.87	0.72	0.87	0.77	0.91	0.93	0.90	0.82	0.72	0.79	1.00	0.74	0.29	0.93	0.80	0.82	0.92	0.92		0.82
POLAND	0.76	0.80	0.63	0.54	0.37	0.75	0.83	0.61	0.71	0.84	0.89	0.40	0.81	0.44	0.62	0.53	0.79	0.82	0.54	0.31	0.80	0.74	1.00	-0.04	0.79	0.60	0.35	0.60	0.75		0.64
PORTUGAL	0.14	-0.10	0.38	0.26	0.47	0.40	0.19	0.31	0.34	-0.02	0.08	0.53	0.12	0.33	-0.02	0.54	0.33	0.32	0.12	0.57	-0.05	0.29	-0.04	1.00	0.32	0.52	0.45	0.45	0.25		0.29
ROMANIA	0.80	0.61	0.86	0.82	0.70	0.86	0.92	0.88	0.91	0.71	0.71	0.74	0.75	0.72	0.70	0.83	0.93	0.94	0.67	0.63	0.78	0.93	0.79	0.32	1.00	0.81	0.71	0.83	0.87		0.78
SLOVAK_REPUBLIC	0.67	0.26	0.94	0.78	0.73	0.96	0.82	0.88	0.92	0.43	0.45	0.77	0.77	0.76	0.55	0.87	0.89	0.90	0.73	0.74	0.49	0.80	0.60	0.52	0.81	1.00	0.76	0.79	0.84		0.74
SLOVENIA	0.66	0.04	0.77	0.94	0.94	0.66	0.72	0.90	0.83	0.19	0.17	0.94	0.43	0.93	0.52	0.90	0.78	0.69	0.73	0.79	0.36	0.82	0.35	0.45	0.71	0.76	1.00	0.83	0.74		0.67
SPAIN	0.83	0.43	0.81	0.87	0.92	0.79	0.87	0.86	0.90	0.54	0.51	0.93	0.61	0.89	0.66	0.97	0.85	0.81	0.82	0.89	0.67	0.92	0.60	0.45	0.83	0.79	0.83	1.00	0.85		0.78
SWEDEN	0.88	0.58	0.85	0.82	0.76	0.89	0.90	0.86	0.91	0.72	0.66	0.78	0.84	0.80	0.65	0.85	0.95	0.90	0.78	0.67	0.68	0.92	0.75	0.25	0.87	0.84	0.74	0.85	1.00		0.79
AVERAGE	0.74	0.45	0.76	0.75	0.70	0.76	0.81	0.78	0.82	0.56	0.54	0.73	0.66	0.73	0.62	0.79	0.80	0.79	0.71	0.64	0.64	0.82	0.64	0.29	0.78	0.74	0.67	0.78	0.79		0.70

particular, we permit weak autocorrelation by using a non-parametric specification due to Bloomfield [54]. As earlier mentioned, this model is implicitly determined by its spectral density function, whose log function is similar to the one produced by an AutoRegressive (AR) process, and the autocorrelations decay exponentially fast as in the AR case. In this context of autocorrelated errors, the time trend is statistically significant in the case of Estonia, with a positive slope, while the intercept is significant in 13 countries. Mean reversion occurs now in the cases of Poland (d = 0.71) and Belgium (0.72); the unit root null cannot be rejected for 15 countries (Austria, Bulgaria, Germany, Denmark, Estonia, France, Hungary, Ireland, Luxembourg, Latvia, Malta, Netherlands, Romania, Slovenia and Sweden; and d is found to be higher than 1 in the remaining ten countries (Cyprus, Czech Rep., Spain, Finland, Greece, Croatia, Italia, Lithuania, Portugal and Slovakia), and the highest d occurs in Portugal (1.60).

Even though this study is focused on black carbon only, these empirical results confirm the general CO_2 studies with unit root tests from Christidou et al. [39] and Tiwari et al. [40], or various others that used fractional integration ([16,41,44,46] or [42] among others) that found non-mean reverting patterns with $d > 1$ results in the long term. A rationale for this predominant empirical evidence of persistence, is that factors of black carbon emissions are also persistent. As it is a form of particulate matter generated from the combustion of fossil fuels, since the dawn of the industrial age, fossil fuels have been a key enabler of economic development, providing the fuel that generated most of the world's electricity, powering transportation, and fueling industrial activity [55].

Therefore, as the consumption of these different forms of energy is persistent, black carbon emission is also expected to be persistent in several countries. For instance, several studies have demonstrated that the energy mix dominated by fossil fuels (inclusive of coal, natural gas and oil) consumption are persistent in nature [56]. Moreover, it has also

Table 10
Correlation analysis. Data after 1950.

	AUSTRIA	BELGIUM	BULGARIA	CROATIA	CYPRUS	CZECH_REPUBLIC	DENMARK	ESTONIA	FINLAND	FRANCE	GERMANY	GREECE	HUNGARY	ICELAND	IRELAND	ITALY	LATVIA	LITHUANIA	LUXEMBOURG	MALTA	NETHERLANDS	NORWAY	POLAND	PORTUGAL	ROMANIA	SLOVAK_REPUBLIC	SLOVENIA	SPAIN	SWEDEN		AVERAGE
AUSTRIA	1.00	0.33	0.05	0.28	0.57	0.07	0.46	-0.15	0.32	0.42	0.27	0.60	0.05	0.63	0.39	0.58	0.03	-0.13	0.77	0.46	0.36	0.72	-0.01	0.39	0.10	0.08	0.19	0.65	0.42		0.34
BELGIUM	0.33	1.00	-0.15	-0.75	-0.44	0.15	0.55	-0.73	-0.02	0.95	0.76	-0.41	0.46	-0.36	0.75	-0.24	-0.33	-0.03	0.73	-0.09	0.97	-0.11	0.69	-0.35	-0.19	-0.13	-0.81	-0.03	0.04		0.08
BULGARIA	0.05	-0.15	1.00	0.13	0.14	0.81	0.48	0.66	0.76	0.05	0.37	0.27	0.52	0.15	-0.33	0.48	0.78	0.77	-0.10	0.26	-0.25	0.43	0.25	0.56	0.88	0.83	0.19	0.27	0.81		0.38
CROATIA	0.28	-0.75	0.13	1.00	0.82	-0.15	-0.23	0.59	0.19	-0.66	-0.59	0.81	-0.45	0.80	-0.49	0.60	0.32	-0.10	-0.15	0.38	-0.67	0.60	-0.73	0.59	0.20	0.11	0.93	0.48	0.17		0.14
CYPRUS	0.57	-0.44	0.14	0.82	1.00	-0.06	-0.03	0.37	0.30	-0.37	-0.38	0.96	-0.42	0.92	-0.24	0.83	0.19	-0.13	0.17	0.67	-0.38	0.74	-0.68	0.71	0.19	0.15	0.80	0.81	0.34		0.26
CZECH_REPUBLIC	0.07	0.15	0.81	-0.15	-0.06	1.00	0.75	0.46	0.89	0.32	0.64	0.10	0.73	-0.07	0.00	0.44	0.82	0.93	0.05	0.26	0.08	0.40	0.57	0.57	0.83	0.94	-0.02	0.25	0.81		0.43
DENMARK	0.46	0.55	0.48	-0.23	-0.03	0.75	1.00	-0.02	0.71	0.68	0.77	0.10	0.65	0.03	0.35	0.37	0.50	0.57	0.57	0.19	0.54	0.49	0.67	0.36	0.50	0.60	-0.23	0.32	0.73		0.43
ESTONIA	-0.15	-0.73	0.66	0.59	0.37	0.46	-0.02	1.00	0.58	-0.59	-0.21	0.43	0.10	0.28	-0.73	0.52	0.74	0.59	-0.52	0.34	-0.75	0.37	-0.27	0.65	0.73	0.67	0.70	0.26	0.45		0.22
FINLAND	0.32	-0.02	0.76	0.19	0.30	0.89	0.71	0.58	1.00	0.18	0.49	0.45	0.57	0.26	-0.09	0.73	0.85	0.82	0.15	0.51	-0.03	0.68	0.30	0.82	0.83	0.94	0.29	0.53	0.84		0.51
FRANCE	0.42	0.95	0.05	-0.66	-0.37	0.32	0.68	-0.59	0.18	1.00	0.88	-0.32	0.64	-0.28	0.68	-0.13	-0.11	0.11	0.76	-0.11	0.90	0.07	0.78	-0.22	-0.03	0.05	-0.74	0.00	0.25		0.18
GERMANY	0.27	0.76	0.37	-0.59	-0.38	0.64	0.77	-0.21	0.49	0.88	1.00	-0.29	0.90	-0.35	0.41	0.01	0.22	0.45	0.56	-0.04	0.70	0.16	0.87	0.01	0.32	0.40	-0.61	-0.01	0.43		0.28
GREECE	0.60	-0.41	0.27	0.81	0.96	0.10	0.10	0.43	0.45	-0.32	-0.29	1.00	-0.30	0.92	-0.18	0.90	0.34	0.04	0.17	0.72	-0.35	0.84	-0.58	0.83	0.34	0.31	0.80	0.84	0.47		0.34
HUNGARY	0.05	0.46	0.52	-0.45	-0.42	0.73	0.65	0.10	0.57	0.64	0.90	-0.30	1.00	-0.38	0.12	0.01	0.42	0.60	0.25	-0.13	0.40	0.17	0.82	0.09	0.49	0.54	-0.43	-0.14	0.45		0.27
ICELAND	0.63	-0.36	0.15	0.80	0.92	-0.07	0.03	0.28	0.26	-0.28	-0.35	0.92	-0.38	1.00	-0.10	0.75	0.19	-0.15	0.26	0.53	-0.29	0.79	-0.58	0.64	0.16	0.09	0.74	0.73	0.37		0.26
IRELAND	0.39	0.75	-0.33	-0.49	-0.24	0.00	0.35	-0.73	-0.09	0.68	0.41	-0.18	0.12	-0.10	1.00	-0.14	-0.28	-0.11	0.56	-0.05	0.76	0.02	0.44	-0.19	-0.33	-0.17	-0.53	0.02	0.03		0.05
ITALY	0.58	-0.24	0.48	0.60	0.83	0.44	0.37	0.52	0.73	-0.13	0.01	0.90	0.01	0.75	-0.14	1.00	0.53	0.36	0.21	0.84	-0.21	0.85	-0.32	0.94	0.59	0.60	0.67	0.92	0.67		0.46
LATVIA	0.03	-0.33	0.78	0.32	0.19	0.82	0.50	0.74	0.85	-0.11	0.22	0.34	0.42	0.19	-0.28	0.53	1.00	0.86	-0.19	0.25	-0.35	0.51	0.20	0.72	0.80	0.91	0.39	0.26	0.76		0.39
LITHUANIA	-0.13	-0.03	0.77	-0.10	-0.13	0.93	0.57	0.59	0.82	0.11	0.45	0.04	0.60	-0.15	-0.11	0.36	0.86	1.00	-0.19	0.23	-0.09	0.24	0.45	0.54	0.81	0.93	0.05	0.16	0.69		0.35
LUXEMBOURG	0.77	0.73	-0.10	-0.15	0.17	0.05	0.57	-0.52	0.15	0.76	0.56	0.17	0.25	0.26	0.56	0.21	-0.19	-0.19	1.00	0.17	0.76	0.39	0.34	0.02	-0.14	-0.11	-0.33	0.38	0.21		0.23
MALTA	0.46	-0.09	0.26	0.38	0.67	0.26	0.19	0.34	0.51	-0.11	-0.04	0.72	-0.13	0.53	-0.05	0.84	0.25	0.23	0.17	1.00	-0.07	0.55	-0.38	0.74	0.43	0.40	0.49	0.89	0.41		0.34
NETHERLANDS	0.36	0.97	-0.25	-0.67	-0.38	0.08	0.54	-0.75	-0.03	0.90	0.70	-0.35	0.40	-0.29	0.76	-0.21	-0.35	-0.09	0.76	-0.07	1.00	-0.06	0.63	-0.33	-0.27	-0.18	-0.75	0.01	-0.03		0.07
NORWAY	0.72	-0.11	0.43	0.60	0.74	0.40	0.49	0.37	0.68	0.07	0.16	0.84	0.17	0.79	0.02	0.85	0.51	0.24	0.39	0.55	-0.06	1.00	-0.13	0.80	0.47	0.49	0.58	0.73	0.70		0.46
POLAND	-0.01	0.69	0.25	-0.73	-0.68	0.57	0.67	-0.27	0.30	0.78	0.87	-0.58	0.82	-0.58	0.44	-0.32	0.20	0.45	0.34	-0.38	0.63	-0.13	1.00	-0.24	0.21	0.31	-0.72	-0.37	0.28		0.13
PORTUGAL	0.39	-0.35	0.56	0.59	0.71	0.57	0.36	0.65	0.82	-0.22	0.01	0.83	0.09	0.64	-0.19	0.94	0.72	0.54	0.02	0.74	-0.33	0.80	-0.24	1.00	0.67	0.75	0.69	0.77	0.69		0.46
ROMANIA	0.10	-0.19	0.88	0.20	0.19	0.83	0.50	0.73	0.83	-0.03	0.32	0.34	0.49	0.16	-0.33	0.59	0.80	0.81	-0.14	0.43	-0.27	0.47	0.21	0.67	1.00	0.88	0.33	0.39	0.79		0.41
SLOVAK_REPUBLIC	0.08	-0.13	0.83	0.11	0.15	0.94	0.60	0.67	0.94	0.05	0.40	0.31	0.54	0.09	-0.17	0.60	0.91	0.93	-0.11	0.40	-0.18	0.49	0.31	0.75	0.88	1.00	0.26	0.36	0.82		0.44
SLOVENIA	0.19	-0.81	0.19	0.93	0.80	-0.02	-0.23	0.70	0.29	-0.74	-0.61	0.80	-0.43	0.74	-0.53	0.67	0.39	0.05	-0.33	0.49	-0.75	0.58	-0.72	0.69	0.33	0.26	1.00	0.51	0.25		0.16
SPAIN	0.65	-0.03	0.27	0.48	0.81	0.25	0.32	0.26	0.53	0.00	-0.01	0.84	-0.14	0.73	0.02	0.92	0.26	0.16	0.38	0.89	0.01	0.73	-0.37	0.77	0.39	0.36	0.51	1.00	0.50		0.40
SWEDEN	0.42	0.04	0.81	0.17	0.34	0.81	0.73	0.45	0.84	0.25	0.43	0.47	0.45	0.37	0.03	0.67	0.76	0.69	0.21	0.41	-0.03	0.70	0.28	0.69	0.79	0.82	0.25	0.50	1.00		0.49
AVERAGE	0.34	0.08	0.38	0.14	0.26	0.43	0.43	0.22	0.51	0.18	0.28	0.34	0.27	0.26	0.05	0.46	0.39	0.35	0.23	0.34	0.07	0.46	0.13	0.46	0.41	0.44	0.16	0.40	0.49		0.31

been observed that wood and biomass fuels consumption are a nonstationary series [57]. More recently, Solarin et al. [58] pointed out that a regression exercise that is affected by variables that are persistent will absorb this persistence from the regressors. Therefore, as black carbon emissions are affected by series such as GDP and population [59] and these variables have been found to be persistent by Gil-Alana et al. [60], it is only logical that black carbon emissions are also found to be persistent in the long term.

However, in recent times this relationship is changing. As can be seen in Figs. 1 and 2, all countries under analysis have had maximums between 1950 and 2000 and some some authors found evidence of mean reversion properties after the year 2000 (Claudio-Quiroga et al., 2022 or [6] among others). The main reasons behind these changes were steady improvements in the energy intensity of economic growth (less energy is required to produce an additional unit of GDP) and, more recently, a dramatic rise in clean energy deployment, there has been a growing divergence between GDP growth and CO_2 emissions in most economies around the world [55].

Therefore, although this study was focused on the long term (1820–2019), we have also estimated in Table 8 the structural breaks to check if recent short-term policies could imply a major impact in the statistical behaviour of the series. Following the Bai-Perron [61] methodology for these estimations, we found evidence of no structural breaks after year 1981. In particular, most of these breaks belong to the WWI and WWII post-war era and during the early 80's for small former Soviet countries. Furthermore, we have estimated the d value in the most recent subperiod, and despite the values per country showing small changes to previous ones, we have obtained an average d value of 1.11, analogous to previous values. Thus, we believe that further efforts are required by policymakers to change the long-term pattern of CO_2 emissions and proceed with current emission patterns.

Finally, in Tables 9 and 10, we have analyzed with a correlation table the possible dependencies between countries using the whole dataset and with data after 1950s to see possible pattern changes. For the whole data, the correlation matrix shows a high degree of relationship (average between all countries 0.70), a figure that is even stronger for related countries (for instance, Baltic countries have a correlation of 0.94). However, what appears interesting is that this average degree of correlation has decreased from 0.70 to 0.31 (Baltic countries 0.64) with data starting in the 1950s after WWII. This fact would imply a higher degree of independency between countries in terms of black carbon emissions.

5. Concluding comments

In this paper we have examined black carbon emissions persistence in the long term for the 27 EU countries. For this purpose, we have analyzed black carbon emissions for the period 1820–2019 with yearly samples. The main contributions of this paper are twofold. First, the study of these specific black carbon emissions in the long term, as most previous analysis were focused on general CO_2 emissions; and second, the extension of traditional analysis based on stationarity I(0) and unit root I(1) tests for long term emissions with fractional integration techniques allowing a non-integer value of the differencing parameter d which enables more intuitive interpretation. The structure of this parameter allows us to analyze if emissions are expected to be corrected naturally, showing mean reversion or, if, on the contrary, shocks have permanent effects in the series.

Empirical results show, in general terms, very high levels of persistence. When assuming white noise, the hypothesis of mean reversion ($d < 1$) cannot be rejected in only four countries (Poland, Ireland, Malta and Denmark) while for the rest of the cases, the unit root null hypothesis ($d = 1$) cannot be rejected in nine countries or it is rejected in favour of $d > 1$ in the remaining fourteen countries. With autocorrelation errors, evidence of mean reversion properties are only observed in the cases of Poland and Belgium while for the rest of the cases, the unit root null hypothesis cannot be rejected in fourteen countries, or if rejected, it is in favour of $d > 1$ in the remaining ten.

In any case, when mean reverting properties are observed, it is in a small set of countries, and with a range of values ($0.5 < d < 1$) that support the hypothesis a slow process in the long term, as shocks are expected to have transitory effects and decay hyperbolically to zero. As for the rest of cases, shocks are expected to be persistent with no mean reverting properties (even in the most recent subseries), we believe that these results support the clear need to introduce further policies to change the long-term pattern and ensure a decline in black carbon emissions across the EU countries. These policies might include additional improvements in diesel filter technologies in shipping and motor vehicles, reforms of motor vehicle emissions standards and testing procedures in the EU countries or more ambitious local-level strategies to condition motor vehicle usage depending on pollution environments. For reaching effective policy outcomes, international agencies, non-governmental organizations, industries, and government agencies should be involved in the black carbon emission mitigation policy formulation and implementation.

Finally, to analyze the impact of recent policies, especially after the year 2000, we have analyzed the potential presence of structural breaks to check if the recent policies had had a major impact in the long-term statistical behaviour of the series. We found that most of these breaks belonged to the WWI and WWII post-war era, and no structural breaks occurred after the year 1981. Therefore, as pointed out before, we consider that further efforts are needed to change the long-term pattern of black carbon emissions. In addition, we have analyzed dependencies between countries with a simple correlation analysis, finding evidence of higher values in the long term (0.7 in average) than in recent times (0.3 in average after 1950). Nevertheless, the issue of breaks may produce abrupt changes in the model and alternative approaches like those based on Markov changes [62] and other non-linear structures can be considered still in this context of fractional integration. Examples are the Chebyshev polynomials in time [63], Fourier functions [64] or neural networks [65]. Work in these directions is now in progress.

Author contribution

S.S. proposed the original idea. He conducted the interpretation of the results, the conclusions and overview of the manuscript, L.A.G.A conducted the empirical results and conclusions, M.G. made the introduction and literature review, M.A.M.V. obtained the data and interpreted results and conclusions.

Declaration of competing interest

There is no conflict of interest with the publication of the present manuscript.

Data availability

Data will be made available on request.

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