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ORIGINAL PAPER

On the examination of the decoupling effect of air pollutants from economic growth: a convergence analysis for the US

Michael L. Polemis[1,2,3] · **Panagiotis Fotis**[2,3] · **Panayiotis G. Tzeremes**[4] · **Nickolaos G. Tzeremes**[5]

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Abstract

The scope of this study is twofold. First, three alternative decoupling indicators associated with the related global (carbon dioxide emissions) and local air pollutants (e.g., sulfur dioxide and nitrogen oxide emissions) for the US regions are estimated over the period 1990–2017 based on eight related decoupling criteria. Second, by employing the Phillips and Sul methodology, we examine for the first time in the literature whether the three decoupling indicators converge among the US regions. The adopted algorithm rejects the convergence hypothesis for the whole sample, leaving room for the existence of several formulated clubs among the US regions. The findings indicate that for the carbon dioxide decoupling indicator three (merged) US regions converge to a steady state, while for sulfur dioxide and nitrogen oxide, two and seven convergence (merged) clubs are present. The transition paths validate the convergence test results. Lastly, this study puts forward some useful policy implications.

Keywords Energy · Decoupling · Convergence analysis · Air pollutants · Economic growth

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✉ Michael L. Polemis
mpolemis@unipi.gr

Panayiotis G. Tzeremes
tzeremes@uth.gr

Nickolaos G. Tzeremes
bus9nt@econ.uth.gr

[1] Department of Economics, University of Piraeus, Piraeus, Greece

[2] Hellenic Competition Commission, Athens, Greece

[3] Hellenic Open University, Patras, Greece

[4] Department of Accounting and Finance, University of Thessaly, Vólos, Greece

[5] Department of Economics, University of Thessaly, Vólos, Greece

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1 Introduction

The term decoupling was first adapted to literature by Zhang (2000) and presented as an indicator by the OECD (2002) report, which distinguishes between two types of decoupling effect: the absolute (when the environmental variable moves in the opposite direction from the economic growth at a stable or decreasing trend) and the relative (when the environmental variable is positive but at a slower rate than the growth of economic activity) decoupling effect. It is used to characterize the link between economic growth and environmental degradation (see Kemp-Benedict 2018; Qian et al. 2020). In other words, decoupling presents a disruption between the rate of growth of environmental damage and economic growth in each period. According to UNEP (2011), the impact of decoupling is referring to a growth path under which a region can increase its economic growth by having specific policies under which the environmental pressures will deteriorate.

Tapio (2005) presents a theoretical framework by defining the difference between decoupling, coupling, and negative as well as weak, strong, and expansive/recessive degrees of decoupling. Particularly, the growth of the variables under scrutiny (environmental & economic activity) can be positive or negative, expressed as expansive coupling (growing link) and recessive coupling (recession link), while decoupling may be divided into three categories such as weak, strong, and recessive decoupling. Negative decoupling may also be broken down into strong, weak, and expansive negative decoupling. Briefly, studies on the decoupling effect fall into four main categories. First, there exist studies examining decoupling factors in a large set of countries with little or no sectoral disaggregation and a specific environmental variable, that is, mainly CO_2 emissions; second, there exist studies on the decoupling effect in specific sectors of the economy, third, there exist studies on decoupling effect in specific countries and fourth, there exist studies that examine the decoupling factors in a large set of countries with sectoral disaggregation and a set of environmental variables.

In this paper, we evaluate the impact of decoupling on the U.S. regions over the period 1990–2017 by utilizing the concepts of the decoupling effect proposed by Tapio (2005) and the methodological framework of Phillips and Sul (2007, 2009). The latter provides several advantages against the classical tools. Particularly, regression is applied by researchers to test for β-convergence which implies a log-linearized solution to a non-stochastic model with an additive error term. Moreover, β-convergence implies that should state converge to a common equilibrium, the dispersion of the variable under study should disappear in the long run since all states would converge to the same strand. Concerning the panel cointegration or unit-root tests, in which the convergence hypothesis of each pair of states is examined considering each of the potential combinations, they omit to notice convergence when more than one equilibria exist. PS model detects the presence of clubs among the sample and calculates the transition paths to trace similar trends. Finally, it detects the transitional heterogeneity and alleviates the stochastic stationarity which is standard in time series data (Phillips and Sul 2007, 2009).

For this purpose, we use deflated regional GDP data, and we construct the decoupling indices for one global carbon dioxide-CO_2 and two local nitrogen oxides-NO_X and sulfur dioxide-SO_2 pollutants for the 50 U.S. states and the District of Columbia (DC). The contribution of this study is twofold. First, we examine the decoupling effect for the 51 US regions over the period 1990–2017. Second, we use the methodological framework of Phillips and Sul (2007, 2009) to explore the existence of possible convergence clubs. To the best of our knowledge, this is the first study to assess the convergence/divergence hypothesis on the (de)coupling of environmental pressure (ΔCO_2, $\Delta SO_{2,}$ and ΔNO_x) from economic growth (ΔGDP) for the US. As a result, the present work fills the gap in the empirical literature by providing fresh evidence of convergence/divergence among regions with estimated decoupling indicators.

2 Data description and methodology

This section describes the methodology we use to examine the convergence analysis developed by Phillips and Sul (2007, 2009) alongside the sample and variable description. The concept of convergence to long-run equilibrium has its origins in Solow's neoclassical growth model (Solow 1956; Baumol 1986) while it was further developed by Barro and Sala-i-Martin (1992). Phillips and Sul (2007) many years later, proposed the concept of relative convergence, which considers the transition path of each country together with its growth performance to find convergence (see also Govinda et al. 1999; Das 2002; Cialani and Mortazavi 2021). Phillips and Sul (2009) propose an econometric approach that jointly considers an economy's transition path with its growth performance. Similarly, this concept can be easily extended to the literature on convergence in emissions, as institutional decisions (international agreements to reduce emissions at fixed dates) and technology adoption are key factors accounting for the varying performance of different countries (Morales-Lage et al. 2019). The relevant methodological framework is suitable for investigating the decoupling effect on the US states since the P–S approach does not impose any restrictive assumptions on the stochastic stationarity or the trend of the eco-efficiency indicators measuring the convergence in relative terms (Kounetas et al. 2021).

In our analysis, we use emission and GDP data for the U.S. regions over the period 1990–2017.[1] Specifically, to construct the decoupling indices we utilize one global carbon dioxide-CO_2 and two local nitrogen oxides-NO_X and sulfur dioxide-SO_2 pollutants for the 50 U.S. states and the District of Columbia (DC).[2]

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[1] We used this period due to limitation of data set.

[2] Alaska (AK), Alabama (AL), Arkansas (AR), Arizona (AZ), California (CA), Colorado (CO), Connecticut (CT), Delaware (DE), Florida (FL), Georgia (GA), Hawaii (HI), Iowa (IA), Idaho (ID), Illinois (IL), Indiana (IN), Kansas (KS), Kentucky (KY), Louisiana (LA), Massachusetts (MA), Maryland (MD), Maine (ME), Michigan (MI), Minnesota (MS), Missouri (MO), Mississippi (MS), Montana (MT),

Regional GDP has been extracted from the Bureau of Economic Analysis (BEA), is adjusted from inflation, and is measured in millions of 2009 USD. The environmental hazards are measured in metric tons, and they have been extracted from U.S. Energy Information Administration (EIA). The main reason for using CO_2 emissions as the main decoupling indicator in this study stems from the fact that carbon dioxide constitutes one of the main anthropogenic greenhouse gases (GHGs), which is regulated under the Paris Agreement for combating climate change worldwide. Additionally, we choose to use two other local air pollutants such as SO_2 and NOx emissions. These gases, especially SO_2, are emitted by the burning of fossil fuels—coal, oil, and diesel—or other materials that contain sulfur. Sources include power plants, metal processing, smelting facilities, and vehicles. NOx emissions are formulated in the atmosphere when fuel is burned at high temperatures. NOx pollution is emitted by automobiles, trucks, and various non-road vehicles (e.g., construction equipment, boats, etc.) as well as industrial sources such as power plants, industrial boilers, cement kilns, and turbines.

To evaluate the impact of decoupling several studies suggest that the first stage is to perform a decoupling analysis by constructing the decoupling indices-DI (De Freitas and Kaneko 2011; Yang et al. 2018; Yang and Yang 2019). The decoupling indices (DI) of the three pollutants can be expressed as:

$$\omega\left(CO_2, GDP\right) = \frac{\frac{\Delta CO_2}{CO_2}}{\frac{\Delta GDP}{GDP}}, \quad \omega\left(SO_2, GDP\right) = \frac{\frac{\Delta SO_2}{SO_2}}{\frac{\Delta GDP}{GDP}}, \quad \omega\left(NO_X, GDP\right) = \frac{\frac{\Delta NO_X}{NO_X}}{\frac{\Delta GDP}{GDP}}. \tag{1}$$

The index represents the ratio of the changes in pollutants over the changes in GDP. The obtained value represents the DI for every pollutant. In our analysis, we construct the DIs on a non-overlapping year-by-year basis (i.e. 1990–1991, 1992–1993, 1994–1995,…, 2016–2017). Table 1 presents all possible classifications of the estimated decoupling indices (see Tapio 2005).

Specifically, we have eight different classifications namely "Expansionary Negative Decoupling"; "Strong Negative Decoupling"; "Weak Negative Decoupling"; "Weak Decoupling"; "Strong Decoupling"; "Recession Decoupling"; "Growing Link" and "Recession Link". For instance, if among two time periods we obtain $\Delta CO_2 > 0$, $\Delta GDP > 0$, and the DI has a value greater than 1.2, then the state of the region is facing an "*Expansionary Negative Decoupling*" of CO_2 emissions. In another case, if a region among two time periods has $\Delta SO_2 < 0$, $\Delta GDP > 0$, and the DI value less than 0, then the state of the region is facing a "*Strong Decoupling*" of SO_2 emissions. This case occurs when a region increases its GDP growth rate while decreasing its level of SO_2 emissions.

Footnote 2 (continued)

North Carolina (NC), North Dakota (ND), Nebraska (NE), New Hampshire (NH), New Jersey (NJ), New Mexico (NM), Nevada (NV), New York (NY), Ohio (OH), Oklahoma (OK), Oregon (OR), Pennsylvania (PA), Rhode Island (RI), South Carolina (SC), South Dakota (SD), Tennessee (TN), Texas (TX), Utah (UT), Virginia (VA), Vermont (VT), Washington (WA), Wisconsin (WI), West Virginia (WV), Wyoming (WY).

Table 1 Decoupling criteria. *Source*: Tapio (2005)

Environmental pressures					
CO_2	NO_X	SO_2	*GDP*	*Decoupling Index-DI*	*Characterization*
$\Delta CO_2 > 0$	$\Delta NO_X > 0$	$\Delta SO_2 > 0$	$\Delta GDP > 0$	$\omega > 1.2$	*Expansionary Negative Decoupling*
$\Delta CO_2 > 0$	$\Delta NO_X > 0$	$\Delta SO_2 > 0$	$\Delta GDP < 0$	$\omega < 0$	*Strong Negative Decoupling*
$\Delta CO_2 < 0$	$\Delta NO_X < 0$	$\Delta SO_2 < 0$	$\Delta GDP < 0$	$0 \leq \omega \leq 0.8$	*Weak Negative Decoupling*
$\Delta CO_2 > 0$	$\Delta NO_X > 0$	$\Delta SO_2 > 0$	$\Delta GDP > 0$	$0 \leq \omega \leq 0.8$	*Weak Decoupling*
$\Delta CO_2 < 0$	$\Delta NO_X < 0$	$\Delta SO_2 < 0$	$\Delta GDP > 0$	$\omega < 0$	*Strong Decoupling*
$\Delta CO_2 < 0$	$\Delta NO_X < 0$	$\Delta SO_2 < 0$	$\Delta GDP < 0$	$\omega > 1.2$	*Recession Decoupling*
$\Delta CO_2 > 0$	$\Delta NO_X > 0$	$\Delta SO_2 > 0$	$\Delta GDP > 0$	$0.8 \leq \omega \leq 1.2$	*Growing Link*
$\Delta CO_2 < 0$	$\Delta NO_X < 0$	$\Delta SO_2 < 0$	$\Delta GDP < 0$	$0.8 \leq \omega \leq 1.2$	*Recession Link*

Furthermore, we utilize Phillips and Sul (2007, 2009) methodological framework, to explore the existence of convergence clubs among U.S. regions' estimated decoupling indices over the examined period. The convergence analysis starts by letting first a single factor model be expressed as:

$$\omega_{i,t} = \varphi_{i,t}\lambda_t. \tag{2}$$

The factor φ_i measures the distance among the systematic part of $\omega_{i,t}$ and the common factor λ_t. It must be noted that both the $\varphi_{i,t}$ and λ_t are time-varying and the behavior of $\varphi_{i,t}$. According to Phillips and Sul (2007), the transition coefficient can be expressed as:

$$\mu_{it} = \frac{\omega_{i,t}}{1/N\sum_{i=1}^{N}\omega_{i,t}} = \frac{\varphi_{i,t}}{1/N\sum_{i=1}^{N}\varphi_{i,t}}. \tag{3}$$

Equation (3) measures the transition coefficient $\varphi_{i,t}$ to the panel average at time t and μ_{it} is called a relative transition parameter. Phillips and Sul (2007, p. 1780) explain that μ_{it} has by a definition a cross-sectional mean of unity and when $\varphi_{i,t}$ convergences to φ_i, implies that it also μ_{it} convergences to unity. In the latter case the cross-sectional variance of $\varphi_{i,t}\left(\sigma_t^2\right)$ convergences to zero in the long run, formally we have that:

$$\sigma_t^2 = \frac{1}{N\sum_{i=1}^{N}\left(\mu_{it} - 1\right)^2} \to 0 \text{as } t \to 0 \tag{4}$$

As described by Phillips and Sul (2007), we need several steps to perform a regression test for convergence. The t test of the null hypothesis of convergence suggests that:

$\mathcal{H}_0 : \varphi_i = \varphi$ and $\alpha \geq 0$, whereas the alternative suggests $\mathcal{H}_1 : \varphi_i \neq \varphi$ for all i or $\alpha < 0$.

Let the cross-sectional variance ratio M_1/M_t, where:

$$M_t = \frac{1}{N\sum_{i=1}^{N}\left(\mu_{it} - 1\right)^2}, \quad \mu_{it} = \frac{\omega_{i,t}}{1/N\sum_{i=1}^{N}\omega_{i,t}} \tag{5}$$

Then by utilizing the following regression we estimate a t statistic $\left(t_{\hat{\beta}}\right)$ for $\hat{\beta}$ as:

$$\log\left(M_1/M_t\right) - 2\log L(t) = \hat{\alpha} + \hat{\beta}\log t + \hat{u}_t, \quad \text{for} \quad t = [\rho T], [\rho T] + 1, \ldots, T \quad \text{with} \quad \rho > 0 \tag{6}$$

Notice that in the regression presented in (6) we use $L(t) = \log(t + 1)$, $\hat{\beta} = 2\hat{\alpha}$ and $\rho = 0.3$. Finally, at the 5% level, the null hypothesis of convergence is rejected if $t_{\hat{\beta}} < -1.65$. The convergence hypothesis implies that $\mu_{it} \rightarrow 1$ and $\mathrm{M}_t \rightarrow 0$ as $t \rightarrow \infty$.

3 Empirical findings

This section presents the empirical results of the study. In the first stage, we present the results of the DIs based on the eight decoupling criteria as suggested by Tapio (2005) generated for the 51 US regions over the period 1990–2017. Then in the second stage, we test for club formulation convergence between the sample regions utilizing the P–S convergence algorithm.

3.1 Evolution of decoupling indicators

Table 2 illustrates the classification of the US regions into eight decoupling regimes as is firstly indicated by Tapio (2005). A careful look at the relevant tables uncovers some interesting remarks. Regarding the CO_2 decoupling indicator, it is evident that nearly 17 US regions (California, Colorado, District Columbia, Delaware, Georgia, Hawaii, Kansas, Maine, North Carolina, New Hampshire, Nevada, Pennsylvania, South Dakota, Tennessee, Texas, Utah, and Washington) have strongly decoupled their CO_2 emissions ("*leaders*") from economic growth since the relevant decoupling indicator/ratio (ω) though negative dictates that the emissions growth rate is negative (numerator) compared to the positive growth rates (denominator).

As it is evident from the relevant table, in these regions, the strong decoupling criterion prevails over the rest seven criteria for the sample period (1990–2017). This translates into significant progress toward tackling climate change at the regional level regardless of federal policy. This could be attributed to several important drivers. First, technological progress alongside the regional environmental policies has allowed some US states to reduce their carbon dioxide emissions. Second, other factors including the major shift from "dirty" energy resources (fossil fuels) to "cleaner" ones (natural gas, renewables) especially in the electricity generation sector in tandem with more stringent energy-efficient regulations (e.g., efficiency standards for buildings and vehicles, lighting, and appliances, etc.) have also played a key role on enhancing the decoupling effect. Moreover, the decarbonization of the electricity sector with the substitution of gas for coal plays also a crucial role in decoupling policy efforts. It is noteworthy that in a few states such as Georgia, North Carolina, and Delaware, the decline in carbon intensity came mostly from

Table 2 Diachronic count of regions' decoupling state for CO_2, NO_X and SO_2 emissions

Regions	Expansionary negative decoupling			Strong negative decoupling			Weak negative decoupling			Weak decoupling			Strong decoupling			Recession decoupling			Growing link			Recession link		
	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2
AK	4	6	4	2	4	0	2	0	0	0	0	2	4	2	2	2	2	6	0	0	0	0	0	0
AL	6	2	2	0	0	0	0	0	0	4	0	2	4	12	10	0	0	0	0	0	0	0	0	0
AR	4	2	4	2	2	0	0	0	2	6	2	2	2	4	4	0	0	0	0	4	2	0	0	0
AZ	4	4	4	0	0	0	0	0	0	4	4	0	6	6	10	0	0	0	0	0	0	0	0	0
CA	2	6	6	0	0	0	0	0	0	0	2	0	8	4	6	2	2	2	2	0	0	0	0	0
CO	0	0	0	0	0	0	0	0	0	2	2	2	10	12	12	0	0	0	2	0	0	0	0	0
CT	4	0	2	0	0	0	0	2	0	0	0	0	6	10	8	2	2	4	0	0	0	2	0	0
DC	0	2	2	0	2	0	0	0	0	0	4	0	10	4	6	4	2	4	0	0	0	0	0	0
DE	2	2	2	2	2	2	0	0	0	0	2	0	10	8	10	0	0	0	0	0	0	0	0	0
FL	4	2	2	0	0	0	0	0	0	2	2	2	4	8	8	2	2	2	2	0	0	0	0	0
GA	4	0	2	0	0	0	0	0	0	2	0	0	8	14	12	0	0	0	0	0	0	0	0	0
HI	0	0	2	2	2	2	0	0	0	2	2	6	10	10	4	0	0	0	0	0	0	0	0	0
IA	6	2	2	0	0	0	0	0	0	2	0	4	6	12	8	0	0	0	0	0	0	0	0	0
ID	8	2	4	0	0	0	0	0	0	2	2	0	2	6	8	2	2	2	0	2	0	0	0	0
IL	2	0	0	2	2	0	0	0	0	4	0	0	6	12	10	0	0	2	0	0	2	0	0	0
IN	0	0	2	0	0	0	0	0	0	6	0	0	6	12	8	2	2	2	0	0	2	0	0	0
KS	4	2	4	0	0	0	0	0	0	2	0	4	8	12	6	0	0	0	0	0	0	0	0	0
KY	2	4	4	0	2	0	0	0	0	0	2	0	6	6	8	0	0	2	4	0	0	2	0	0
LA	0	0	2	6	4	2	0	2	0	6	0	0	0	4	4	2	2	4	0	2	0	0	0	2
MA	4	2	4	2	2	2	0	0	0	0	0	0	6	10	8	0	0	0	2	0	0	0	0	0
MD	4	0	4	0	0	0	2	0	0	0	2	0	6	10	8	0	2	2	2	0	0	0	0	0
ME	4	8	4	0	2	2	0	0	0	0	0	2	4	0	2	6	4	2	0	0	0	0	0	2
MI	2	0	0	4	4	4	0	0	0	0	0	0	8	10	8	0	0	0	0	0	2	0	0	0

Table 2 (continued)

Regions	Expansionary negative decoupling			Strong negative decoupling			Weak negative decoupling			Weak decoupling			Strong decoupling			Recession decoupling			Growing link			Recession link		
	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2
MN	2	2	2	0	2	0	0	0	0	2	0	0	6	10	8	2	0	2	2	0	2	0	0	0
MO	4	2	2	2	2	0	0	0	0	2	2	0	6	8	10	0	0	2	0	0	0	0	0	0
MS	8	2	2	0	0	0	0	0	0	2	4	0	2	6	10	2	2	2	0	0	0	0	0	0
MT	6	4	8	0	0	0	0	0	0	2	2	4	4	4	2	0	0	0	2	4	0	0	0	0
NC	4	4	2	0	0	0	0	0	0	0	0	2	8	10	10	0	0	0	2	0	0	0	0	0
ND	2	2	2	4	2	2	0	0	0	2	2	0	6	6	6	0	2	2	0	0	2	0	0	0
NE	6	2	4	0	0	0	0	0	0	0	2	4	6	10	2	0	0	0	2	0	4	0	0	0
NH	4	6	2	0	0	2	0	0	0	0	0	2	8	6	8	2	2	0	0	0	0	0	0	0
NJ	8	2	6	2	0	0	0	0	0	0	0	0	2	8	2	2	4	4	0	0	2	0	0	0
NM	4	2	4	0	0	0	0	0	0	4	0	2	6	10	8	0	0	0	0	2	0	0	0	0
NV	4	2	0	2	0	0	0	0	0	0	0	2	8	10	8	0	2	2	0	0	2	0	0	0
NY	6	2	4	0	0	0	0	0	0	2	0	0	2	8	6	4	2	4	0	0	0	0	2	0
OH	4	2	2	2	2	2	0	0	0	2	2	2	6	8	8	0	0	0	0	0	0	0	0	0
OK	4	4	6	0	0	0	0	0	0	2	4	2	6	6	4	0	0	0	2	0	2	0	0	0
OR	8	8	8	0	0	0	0	0	0	2	0	0	4	6	6	0	0	0	0	0	0	0	0	0
PA	0	4	4	0	0	0	0	0	0	4	0	0	8	10	10	0	0	0	2	0	0	0	0	0
RI	2	2	2	6	0	2	0	2	0	0	0	0	6	4	6	0	4	4	0	2	0	0	0	0
SC	4	2	0	0	0	0	0	0	0	2	2	2	6	10	10	0	0	0	2	0	2	0	0	0
SD	6	4	4	0	0	0	0	0	0	0	2	0	8	8	8	0	0	0	0	0	2	0	0	0
TN	2	2	0	0	0	0	0	0	0	0	0	2	10	10	10	0	2	2	0	0	0	2	0	0
TX	2	4	2	0	0	0	0	0	0	4	0	2	8	10	10	0	0	0	0	0	0	0	0	0

Table 2 (continued)

Regions	Expansionary negative decoupling			Strong negative decoupling			Weak negative decoupling			Weak decoupling			Strong decoupling			Recession decoupling			Growing link			Recession link		
	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2	CO_2	NO_x	SO_2
UT	2	0	2	0	0	0	0	0	0	2	2	2	8	12	10	0	0	0	2	0	0	0	0	0
VA	6	4	4	2	2	2	0	0	0	2	0	2	4	8	6	0	0	0	0	0	0	0	0	0
VT	6	4	6	2	2	0	0	0	0	0	0	0	4	6	4	2	2	4	0	0	0	0	0	0
WA	4	4	4	0	0	0	0	0	0	0	0	0	8	10	10	0	0	0	2	0	0	0	0	0
WI	8	0	2	0	0	0	0	0	0	2	2	0	4	12	12	0	0	0	0	0	0	0	0	0
WV	2	2	4	0	0	0	0	0	0	2	0	0	6	10	6	2	2	2	2	0	2	0	0	0
WY	0	0	2	0	2	2	0	0	0	6	2	0	6	10	10	0	0	0	0	0	0	2	0	0

Table 3 Convergence clubs for the whole sample per pollutant (CO_2, SO_2, and NO_x)

Category	log t	t-stat
$\omega(CO_2, GDP)$	– 1.364	– 17.438*
$\omega(SO_2, GDP)$	– 0.680	– 7.817*
$\omega(NO_X, GDP)$	– 2.042	– 16.970*

The critical value is – 1.65, *denotes rejection of the null hypothesis

improvements in energy efficiency in buildings and industries, and the implementation of "*green*" policy strategies shifting from heavy manufacturing to less carbon-intensive service sectors (Saha and Jaeger 2020). On the other hand, regions such as Rhode Island Louisiana, Idaho, Mississippi, New Jersey, Oregon, and Wisconsin have coupled their carbon dioxide emissions volume with economic growth and thus can be characterized as "*laggards*". These regions can be classified into expansionary negative decoupling or strong negative decoupling regimes.

Concerning the diachronic regime state of the NO_x decoupling indicator. A quick look at the relevant table, reveals some important findings. As it is evident, in this case more US regions have achieved strong decoupling effects from economic growth (Alaska, Colorado, Connecticut, Delaware, Florida, Georgia, Hawaii, Iowa, Illinois, Indiana, Kansas, Massachusetts, Maryland, Michigan, Minnesota, Missouri, North Carolina, Nebraska, New Mexico, Nevada, New York, Ohio, Pennsylvania, South Carolina, South Dakota, Tennessee, Texas, Utah, Virginia, Washington, Wisconsin, West Virginia, and Wyoming). Especially for Georgia, it is interesting to note that the strong decoupling criterion prevails across the whole period compared to the rest US regions that fall within this regime.

On the contrary, some regions such as Alaska, California, Maine, New Hampshire, and Oregon can be classified into the "*expansionary negative decoupling*" regime, with the relevant ratio ω greater than 1.2 (elasticity). This means that the (positive) NO_x volume growth is much greater than the (positive) level of economic growth. We also note that the rest of the sample regions do not appear to have a consistent regime. Lastly, similar findings occur when we assess the diachronic SO_2 decoupling indicator (see Table 5).

3.2 Convergence club clustering

The results drawn from the P–S convergence algorithm are illustrated in Table 3. As it is evident, the null hypothesis of convergence cannot be accepted for the full sample (51 US regions) since the t-statistic is smaller than the critical value (– 1.65) at a 5% level of statistical significance.

In other words, we have to infer if separate convergence clubs exist within the US territory. Based on the results of Tables 4, 5 and 6, it is evident that multiple convergence clubs are drawn from the whole sample for the three pollutants (CO_2, SO_2, and NO_X) with an unequal number of states can be formulated). This is based simply on the results of the one-sided hypothesis testing. Specifically, we observe that the value of the convergence coefficient (log t) in each club exceeds the critical

Table 4 Convergence clubs for $\omega\left(CO_2, GDP\right)$

Category	log t	t-stat	New club	Final classification	log t	t-stat
Club 1 [FL,IN,MN,MS,NJ,NM,VT]	0.823	1.853	1 + 2	Club 1	0.021	0.413
Club 2 [AK,AL,AZ,CA,CO,CT,GA,HI,IA, IL,KS,KY,LA,MA,MD,ME,MI,MO,MT, NC,ND,NE,NH,OH,OK,OR,PA,RI, SC, SD,TN,TX,UT,VA,WA,WI,WV,WY]	0.220	2.648				
Club 3 [DE,NV]	0.0154	0.108	3	Club 2	− 0.002	− 0.048
Club 4 [AR,DC]	− 3.608	− 1.587	4	Club 3	− 2.285	− 0.942
Divergent [ID,NY]	− 2.017	− 120.075	–	–	–	–

value of the convergence test statistic (− 1.65) in the one-sided hypothesis testing. This results in the acceptance of the null hypothesis (convergence) at a 5% level of statistical significance. The convergence statistic follows the t-student distribution with n − 1 degrees of freedom.

It can be easily shown that in the case of the CO_2 decoupling indicator, there are four primary convergence clubs (see Table 4, Column 1) consisting of an unequal number of regions. Specifically, Club 1 consists of seven regions (Florida, Indiana, Minnesota, Mississippi, New Jersey, New Mexico, and Vermont). Club 2 has 38 members (Alaska, Alabama, Arizona, California, Colorado, Connecticut, Georgia, Hawaii, Iowa, Illinois, Kansas, Kentucky, Louisiana, Massachusetts, Maryland, Maine, Michigan, Missouri, Montana, North Carolina, North Dakota, Nebraska, New Hampshire, Ohio, Oklahoma, Oregon, Pennsylvania, Rhode Island, South Carolina, South Dakota, Tennessee, Texas, Utah, Virginia, Washington, Wisconsin, West Virginia, and Wisconsin), while Club 3 consists only of two regions, namely Denver and Nevada. Similarly, Club 4 has also two members (Arkansas and District Columbia). On the contrary, two regions (Idaho and New York) formulate a non-converging group. However, for the formulated clubs, we observe that the estimated logt values are greater than the critical value of −1.65 suggesting the existence of a convergence trend of the decoupling effect among the sample US regions.

In the case of the SO_2 decoupling indicator, there are three primary convergence clubs (see Table 5). Club 1 is the largest of all consisting of 42 US regions, while Club 2 has four members namely Arkansas, Connecticut, South Dakota, and Wyoming. Club 3 consists only of two regions, (Mississippi and Rhode Island). On the contrary, two regions (District Columbia and New York) formulate a non-converging group.

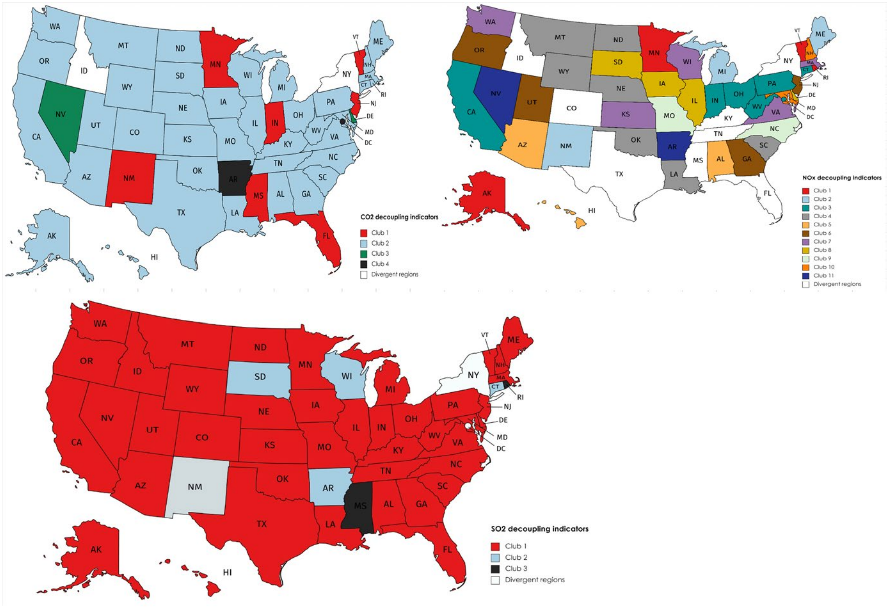
On the contrary, based on the NOx decoupling indicator (Table 6), we identify eleven primary convergence clubs of almost equal size. Based on the estimated values, we cannot reject the null hypothesis of convergence in all the eleven clubs since the t-statistic is larger than the critical value (− 1.65) at a 5% level of statistical significance. The two largest primary convergence clubs (Club 3 and Club 4) consist of seven US regions, while the smallest formulated clubs include only two regions (see Club 9, 10, and 11). Moreover, we notice that spatial clustering can be observed in Club 1 which implies commonalities among the regions within this formulated club (see Fig. 1).

Table 5 Convergence Clubs for $\omega\left(SO_2, GDP\right)$

Category	log t	t-stat	New club	Final classification	log t	t-stat
Club 1 [ID,VT,LA,AK,FL,NJ,MT,NM, OR,MO,NE,TN,WV,OK,MD,GA,UT, AZ,SC,HI,IN,AL,TX, KS,PA,MI,DE,MA,IA,ME,IL, WY,WA,ND,CA,NC,OH,KY, VA,CO,NV,MN,NH]	1.178	9.953	1 + 2	Club 1	0.989	9.842
Club 2 [AR,CT,SD,WI]	1.865	6.459				
Club 3 [MS,RI]	3.764	3.366	3	Club 2	− 2.374	0.099
Divergent [DC,NY]	− 2.469	− 364.584	–	–	–	–

Table 6 Convergence Clubs for $\omega(NO_X, GDP)$

Category	log t	t-stat	New club	Final classification	log t	t-stat
Club 1 [AK,MN,RI,VT]	1.307	7.649	1 + 2	Club 1	0.955	6.337
Club 2 [ME,MI,NM]	0.287	1.944				
Club 3 [CA,CT,DC,IN,OH,PA,WV]	0.287	1.430	3 + 4	Club 2	0.347	2.187
Club 4 [LA,MT,ND,NE,OK,SC,WY]	0.348	1.782				
Club 5 [AL,AZ,HI]	0.738	3.081	5 + 6	Club 3	0.033	0.248
Club 6 [GA,NJ,OR,UT]	0.550	4.157				
Club 7 [KS,MA,VA,WA,WI]	0.148	1.203	7 + 8	Club 4	0.405	2.093
Club 8 [DE,IA,IL,SD]	0.374	3.115				
Club 9 [MO,NC]	1.784	2.192	9	Club 5	0.723	4.368
Club 10 [MD,NH]	0.344	1.247	10	Club 6	−0.208	−1.102
Club 11 [AR,NV]	−0.254	−1.142	11	Club 7	0.223	2.158
Divergent [CO,FL,ID,KY,MS,NY,TN,TX]	−3.266	−71.020	–	–	–	–



Notes: The figure was created with mapchart.net

Fig. 1 Graphical illustration of primary convergence clubs. Notes: The figure was created with mapchart.net

Having delineated the convergence clubs based on P–S (2007) generic algorithm, the analysis proceeds with the interpretation of the speed of convergence (α) among the formulated clusters.[3] A deeper inspection of Table 4 reveals some important findings. First, the speed of convergence is positive and varies significantly across the four primary convergence clubs. However, for Club 4 it is reported a negative speed of adjustment equal to $\alpha = -1{,}804$. Second, the first club, records an absolute value of $\alpha = 0{,}411$ approximately, indicating a high adjustment speed to convergence among other clubs. Third, Club 3 is characterized by a small value of convergence speed equal to $\alpha = 0{,}007$. This means that the two club regions (Denver and Nevada) are approaching one another more slowly in relative terms. It is noteworthy that this value is almost fourteen times greater than the relevant one that appears in Club 2 ($\alpha = 0.11$).

Similarly, in the case of the SO_2 decoupling indicator, we observe a positive convergence speed in all the formulated clubs (see Table 5). However, the speed of convergence varies significantly between the three primary detected clubs, with the formulated Club 3 (Mississippi and Rhode Island) recording the highest speed ($\alpha = 1.882$) and the largest in magnitude Club 1 the lowest ($\alpha = 0.589$). This pattern is fully reversed in the case of the NO_x decoupling indicator. As it is evident from Table 6, we argue that except for Club 11, where the convergence speed is negative ($\alpha = -0.127$), the rest primary clubs have positive convergence speed ranging from 0,074 (Club 7) to 0.892 (Club 9).

We now turn our attention to whether it is possible to merge some of the initial convergence clubs found above. The relevant results are also illustrated in Tables 4, 5 and 6 (see the fourth column). Regarding the CO_2 decoupling indicator (see Table 4), we notice that we fail to reject the null hypothesis of convergence in two cases (Club 1 + 2, and Club 2), revealing that the four primary convergence clubs can be finally reduced to three. As it is evident from the relevant table the first two clubs can be merged into one larger (merged) "*entity*" consisting of 45 US states with low estimated convergence speed ($\alpha = 0.0105$).

Similar findings are evident by examining the SO_2 decoupling indicator (see Table 5). In this case, only the initial convergence Club 1 (Idaho, Vermont, Louisiana, Alaska, Florida, New Jersey, Montana, New Mexico, Oregon, Missouri, Nebraska, Tennessee, West Virginia, Oklahoma, Maryland, Georgia, Utah, Arizona, South Carolina, Hawaii, Indiana, Alabama, Texas, Kansas, Pennsylvania, Michigan, Denver, Massachusetts, Iowa, Maine, Illinois, Wyoming, Washington, North Dakota, California, North Carolina, Ohio, Kentucky, Virginia, Colorado, Nevada, Minnesota, and New Hampshire) and Club 2 (Arkansas, Connecticut, South Dakota, and Wisconsin) can be merged into one and the relevant t-statistic (0.989) is larger than the critical value of -1.65 failing to reject the null hypothesis. On the contrary, the t-statistic (-2.374) in primary Club 3 (Minnesota and Rhode Island) falls outside the acceptance of the null hypothesis region, thus rejecting the convergence hypothesis.

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[3] Based on Phillips and Sul (2007), the speed of convergence α can be calculated as half the estimated convergence coefficient.

A different picture emerges in the case of the NOx decoupling index. It is obvious that after club-merging, there are seven convergence clubs (i.e., primary clubs 9, 10, 11, and four merged Clubs 1 + 2, 3 + 4, 5 + 6, and 7 + 8). Moreover, we reject the null hypothesis of convergence in five cases (Club 1 + 2, Club 3 + 4, Club 7 + 8, Club 9, and Club 11). The existence of seven individual decoupling clubs, in this case, postulates that there is extensive heterogeneity in the sample. This might reflect structural differences either in the regional income level (GDP) or in the environmental policies pursued across the US states (Saha and Jaeger 2020; Camarero et al 2014).

4 Conclusions

The objective of this study is to examine the convergence patterns of decoupling factors of three environmental hazards (CO_2, SO_2, and NO_X) from economic growth across the U.S. regions over the period 1990–2017. By applying the Phillips and Sul (2007, 2009) methodology, we are able to trace convergence clubs and illustrate their transition paths. Specifically, the generic algorithm rejects the convergence hypothesis for the whole sample, justifying the existence of several formulated convergence clubs among the US regions. The empirical findings further elucidate the existence of two "*large*" spatial clusters concerning the CO_2 and SO_2 decoupling indicators (Club 2 and Club 1 respectively). On the opposite, the other local environmental hazard (NO_X emissions) seems to deviate from the "*concentrated*" spatial pattern, since eleven primary convergence clubs are detected across the US territory. This heterogeneity sheds some light on the future direction of the environmental policy that must be pursued by government officials and regulators to combat climate change and successfully decouple the NO_X emissions from the level of regional economic growth.

The empirical analysis in this paper could be useful for government officials and policymakers in their efforts to combat environmental degradation alongside economic growth. This could be achieved by a significant shift from fossil fuels (e.g., coal, oil) to "*clean*" energy resources such as renewables (wind, hydro, solar power) and natural gas. Specifically, in regions with high environmental degradation policymakers should follow a more sustainable path by focusing on ecological conservation and green development. Renewable energy plays a crucial role in this process. Moreover, clubs, where air pollution problems are most prominent, should be formulated with more stringent goals and measures, such as an increase in technological innovation. It is also recommended to strengthen the control of air pollution by reducing NOx emissions from the level of regional economic growth.

Furthermore, in terms of policy implications, our findings suggest that the U.S. economy can be benefited further by enhancing and encouraging low-carbon technology and low-carbon investments. This decoupling process as has been stressed both by Saha and Muro (2016) and Saha and Jaeger (2020) can attract investment opportunities with long-term positive effects for the U.S. economy. In addition, as has been also emphasized by Tsionas and Tzeremes (2022), U.S. policymakers must further enhance the implementation of long and short-term low-carbon policies making them robust to potential pushbacks on low-carbon regulatory structures.

However, this study is not free from limitations. One of the most prominent one is that we examine only three global and local air pollutants, and only one of them (CO_2) is related to global warming and the international climate agreements (e.g., Parris Accord). Therefore, future research could focus on the assessment of all greenhouse gases, to further check and validate the results of this analysis. Lastly, policymakers and government officials should seriously address these issues since the role of decoupling and the (regional/federal) environmental policies to achieve this, is one of the most challenging issues.

Declarations

Conflict of interest The authors declare no conflict of interest.

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