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The long-term relationship between CO_2 emissions and economic activity in a small open economy: Uruguay 1882–2010

Matías Piaggio[a,c], Emilio Padilla[b], Carolina Román[a]

[a]Instituto de Economía, Universidad de la República, 11200 Montevideo (Uruguay)

[b]Department of Applied Economics, Univ. Autónoma de Barcelona, 08193 Bellaterra (Spain)

[c]Environment for Development, Centro Agronómico Tropical de Investigación y Educación, 30501 Turrialba (Costa Rica)

e-mail: matias.piaggio@catie.ac.cr, emilio.padilla@uab.es, croman@iecon.ccee.edu.uy

Abstract

The long-term relationship between carbon dioxide (CO_2) emissions from energy use and economic activity level is estimated for Uruguay between 1882 and 2010. We include CO_2 emissions both in levels and in per capita terms, which allows to analyze if a decoupling exists both in absolute and in relative terms. We also test for the functional form of the relationship, something that is usually missed in the literature, but which is very relevant, because a misspecification could lead to biased estimates. We apply cointegration techniques and estimate a vector error correction model (VECM) for testing whether these variables are endogenous over the long-term while also considering the short-term dynamics. The economic productive structure, the degree of openness, and the share of clean sources in the total energy supply are also considered as explanatory variables. In addition, other variables that measure changes in the economic structure are included to check for robustness of the estimates. The results show that there is a linear relationship (when a log-log transformation is employed) between CO_2 emissions and per capita economic activity level (which would involve an exponential relationship between the non-transformed variables). Moreover, we cannot reject the level-log model, indicating that emissions increase at a decreasing rate in reference to the increase in economic level activity. Emissions increase jointly with the industrial sector's participation in the total output, as a consequence of the intensity of this activity in the consumption of energy from fossil fuel sources. The degree of openness is inversely related to CO_2 emissions. This is because the periods of major opening were based on primary input exports, which are lower in energy intensity than industrial products. The changes in CO_2 emission are inversely related to the variation in the share of clean sources in the total energy supply. Finally, all the variables included in the cointegration vector are endogenous, adjusting together to the deviations from the long-term relationship. As a consequence of the above, economic growth appears not to be enough for diminishing Uruguayan emissions in the long term. Changes in the energy matrix should be encouraged, and emissions reduction should come not through energy constraints but through the development of clean sources, or improvements in energy use efficiency, given the impact of energy on the economic activity level.

Keywords: carbon dioxide, cointegration, Environmental Kuznets Curve, Uruguay.

JEL codes: Q43, C32, Q56

1. Introduction

Since the early 1990s, the debate about the relationship between economic growth and environmental degradation has been dominated by the discussion of the environmental Kuznets curve (EKC) hypothesis. The EKC suggests the existence of an inverted-U shaped relationship between environmental degradation and income per capita. According to Grossman and Krueger (1991) the EKC hypothesis is explained by three effects: i) the scale effect, where the greater the scale the greater the requirement of resources and waste generation; ii) the composition effect, where a growing economy allegedly changes its economic structure towards less polluting activities after achieving a certain income threshold; and iii) the technological effect where richer countries increase their capacity to use technological substitution towards less polluting processes. According to the EKC hypothesis, while the increase in the scale of an economy would contribute to an increase in environmental degradation, the growing importance of the other effects, as the economy grows, would lead to a turning point in the relationship. It should be noted that this hypothesis assumes that both composition and technological effects work in the assumed direction, which would be not the case for all pollutants and economies (Roca and Padilla, 2003). The EKC can also be the result of the displacement of polluting activities from rich to poor countries, a behavior that may not be replicated in the future by the present poorer countries (Stern et al., 1996; Cole et al., 1997). This may be reflected in a positive relationship between emissions and trade in those countries where polluting activities tend to locate, and a negative relationship in those countries that displace the polluting activities, however, there is no consensus about this. If exports are driven by low-polluting activities (such as agrarian products), the relationship between emissions and trade can be the inverse.

Empirical studies on the EKC often only analyze emissions in per capita terms, however, the relevant level of pressure for nature is total pressure, and not per capita pressure, as Luzzatti and Orsini (2009) argue for the case of energy use. In the case of carbon dioxide (CO_2) emissions, the pressure on the environment depends on global emissions, while the variable in per capita terms is only an indicator of the relative contribution and so the responsibility of the inhabitants of different parts of the world. Certainly, the use of the per capita variable has the advantage of giving results that are directly comparable across countries, but its interpretation widely differs from that where the absolute value of emissions is considered.[1] An analogous distinction is made in the literature between relative and absolute decoupling (or weak and strong delinking), referring to variables of environmental pressure intensity (pressure per unit of product) (Opschoor, 1995). An inverted-U shaped relationship between pollution and economic activity in per capita terms cannot be interpreted as evidence that economic growth is sufficient to induce environmental improvement or that the ecospace is large enough to support ongoing economic growth, as this will ignore the impact of population growth.

Most studies of the long-term relationship between environmental degradation or energy use and economic activity level consider periods no longer than 60 years, due to data constraints. Energy (and hence CO_2 emissions) transitions are structural facts, and thus they should be analyzed with a long-term perspective. There are few studies about the relationship between

[1] Even for this purpose, as Luzzati and Orsini (2009, p. 292) argue, in the case of panel data or cross-section analyses, "*comparability would be better obtained by standardizing environmental indicators with a scalar (e.g. inhabited area, population in a given year), rather than a variable, i.e., population time series*". In any case, as we only study the case of Uruguay, using the variable in per capita terms would give us results more directly comparable with the results of previous studies.

energy consumption or pollution and economic activity level for longer periods. For instance, decomposition techniques have been employed by Kander and Lindmark (2004) in Sweden; Bartoletto and Rubio (2008) in Italy and Spain; and Tol et al. (2009) in the USA. Multi-equation models and cointegration analysis have been employed by Esteve and Tamarit (2012a, 2012b) and Sephton and Mann (2013) in Spain; Vaona (2012) in Italy; Barassi and Spagnolo (2012) in Canada, France, Italy, Japan, UK, and USA; and Stern and Enflo (2013) in Sweden.

The present paper analyzes the relationship between CO_2 emissions from energy use and economic activity in Uruguay during the period 1882–2010. The evidence for developing countries is very scarce and a long-run perspective allows to improve our knowledge of these economies and to discuss their specificities. This paper provides evidence for a small open economy of a developing country, which besides its specific interest and usefulness, could be extrapolated to understand the case of similar countries. CO_2 emissions are more relevant than energy use for the analysis of environmental pressures, given that despite these variables can be highly correlated, the later can be provided through clean sources. The analysis has been conducted considering two main aspects that are novel for the literature. First, we use one of the largest time spans used in the literature, in particular for a developing country. Uruguay has experienced great variability in its per capita income over this period, which should facilitate the detection of the influence of these variations on environmental pressure. It is a small open economy with a strong specialization in agricultural products. Transformations in the productive structure ―mainly, the decrease of the primary sector and the increase of manufacturing― and the international integration patterns based on the natural resources products have driven changes in the uses of energy during the 20th century. In order to consider the effect of these factors in explaining the relationship between CO_2 emissions and economic activity, we use two indicators that measure the structural change (that is, the share of the industrial sector in the economy, and a structural change synthetic indicator). The inclusion of different measures of economic structure provides robustness to our analysis. The degree of openness of the economy and the share of clean energy sources are other additional variables considered in the analysis. The Uruguayan case has been previously studied by Piaggio (2008) but for a much shorter period (1950–2000). The time length used in the present study would allow either to confirm the previous results, or to determine whether in the very long term there are other factors driving this relationship that are not present in a shorter period (or vice versa). In addition, including the late 19th century and the first half of the 20th century allow us to study the important transformation of the productive structure that took place during the Import Substitution Industrialization (ISI), between 1930s and 1950s.

Second, we analyze different model specifications. We test for the functional form, something that is usually missed in the literature, but of great importance because a misspecification could lead to biased estimates. In addition, we consider the dependent variable (CO_2 emissions) both in absolute and in per capita terms. This aspect has not been considered before in the EKC empirical literature on CO_2 emissions, making a break in the conceptual thinking of the model. This allows the analysis of the impact on environmental pressure of the relationship between economic activity level and CO_2 emissions, as the contribution of a country to CO_2 atmospheric concentration depends on its absolute and not on its per capita emissions. We also employ cointegration techniques to determine the existence of a long-term relationship between non-stationary variables, and a vector error correction model (VECM) is estimated to allow variables to be endogenous. This overcomes the critique made by Arrow et al. (1995), who argued that early studies ignored the possible feedback between income and the environmental indicator.

Endogenous variables in the long-term would mean that not only are CO_2 emissions explained by economic growth, but that it could also be the other way around. This would have important policy implications, given that a reduction in fossil energy consumption to mitigate emissions could affect economic growth, unless energy efficiency is improved or this energy is substituted by clean sources.

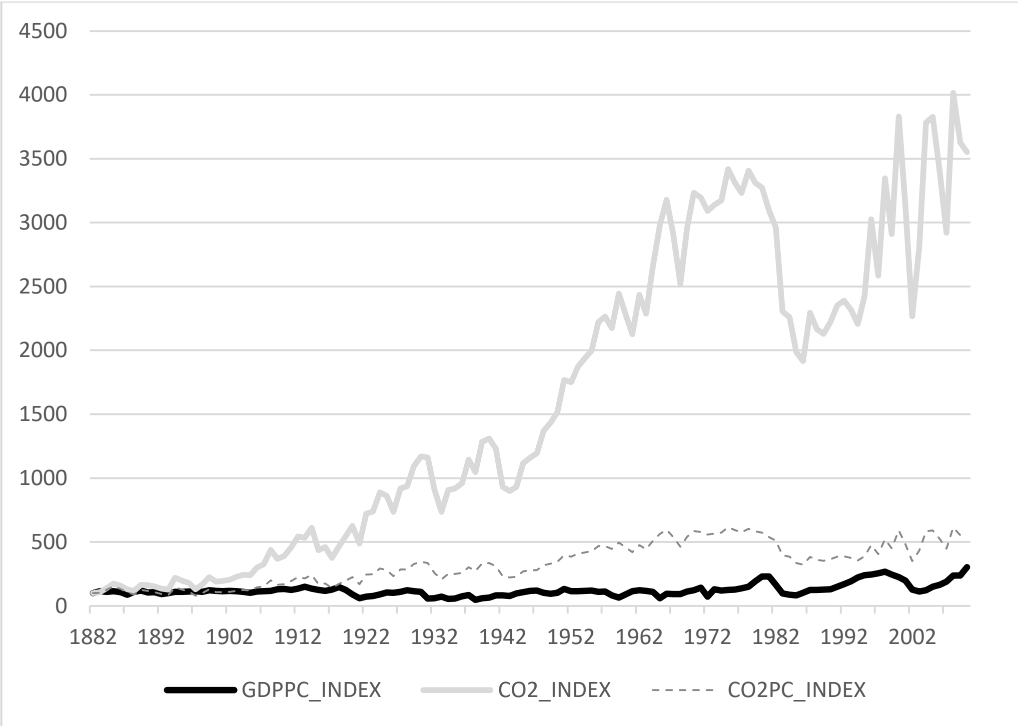
The rest of the paper is organized as follows. Section 2 presents an overview of the Uruguayan economy and describes the evolution of the variables of interest over the last 130 years. Section 3 explains the model specification and the empirical strategy. The data and sources are described in Section 4, and Section 5 presents the results. Finally, Section 6 includes the discussion, main conclusions and the research agenda.

2 An historical overview of the Uruguayan economy

Uruguay is a small Latin American country (around three million inhabitants) in the middle of two large economies: Argentina and Brazil. Since the last decades of the 19th century, the region of Latin America has experienced a dynamic but unstable growth pattern (Bértola and Ocampo 2012). Uruguay, together with Argentina, were the two countries that achieved higher levels of income per capita at the international level at the beginning of the 20th century but showed a divergent pattern —compared to the developed countries— since then. In addition, Uruguay shared some of the structural features of the region, like the pattern of trade specialization based on natural resources products and the volatility of economic growth (Bértola and Ocampo 2012).

The long-term growth rate in the Uruguayan GDP per capita has been quite low (1.3% annual rate of growth over 1882–2010). Phases of rapid growth were followed by deep crises, explained as a cyclical pattern correlated with the volatility of the terms of trade, world demand and international capital flows (Bértola, 2008). Figure 1 describes a divergent path between CO_2 emissions in absolute and per capita terms. While per capita emissions behave very similarly to GDP per capita, pollution in absolute terms diverges. This gap can be explained by the evolution of population that, after a very dynamic phase until the 1930s, became stable in the following decades (immigration almost disappeared and population grew at a very low rates), and where after the 1960s the country was a net-emigration region (Bértola, 2008).

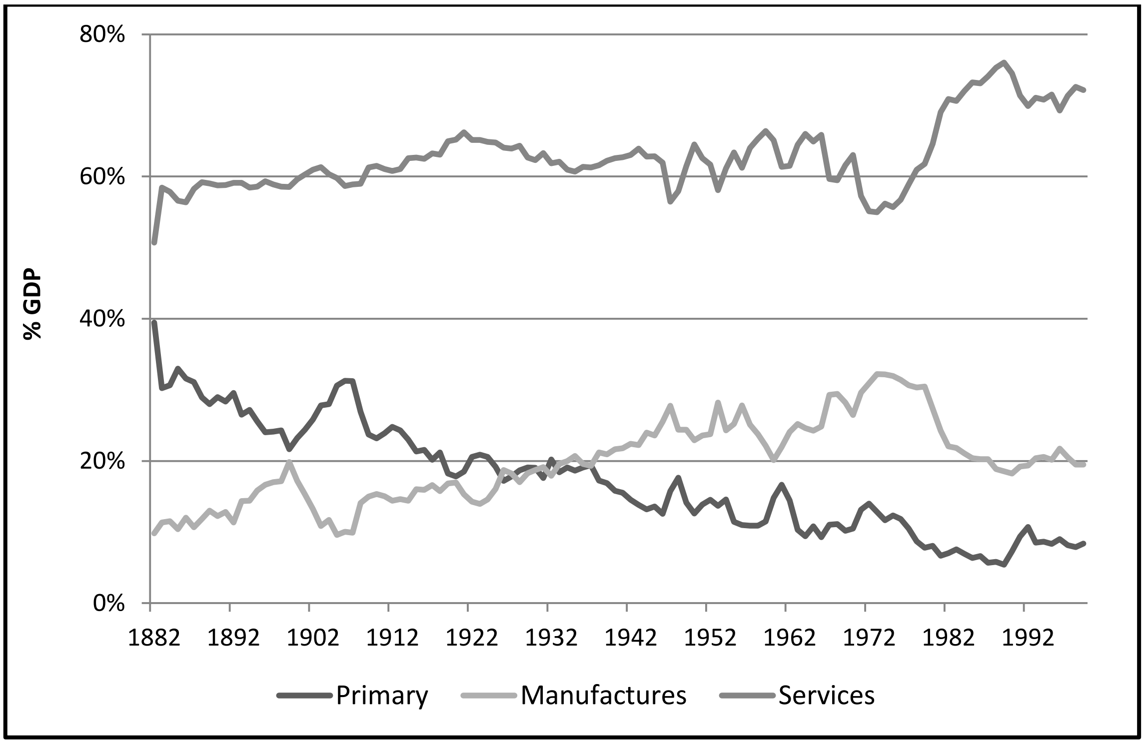
Figure 1: CO_2 emissions, per capita carbon CO_2 and per capita GDP at 2005 constant Uruguayan pesos (Index 1882=100), 1882-2010.



Source: Own elaboration based on Bonino et al. (2012), and Bertoni and Román (2016).

These divergent paths may also be explained by changes in the Uruguayan productive structure over the last century. Economic history identifies three patterns of development (Bértola, 2008). Between the late 19th century and the 1930s, Uruguayan economic growth was led by exports based on a few primary products, and the country achieved high-income levels in comparative international terms. The primary sector represented about one-third of the total economic activity between 1870 and 1930, and the share of the industrial sector was around 15% of GDP (Figure 2). Because of the stock market crash of 1929 and the Great Depression, the country adopted inward-oriented policies and state-led industrialization as a strategy to promote growth. As a result, the share of the industrial sector increased in total output, a trend that lasted until the late 1950s when the country faced a period of stagnation and high inflation. This episode was not overcome until the 1970s with deep changes, increasing openness, financial liberalization and regional trade agreements. A new strategy to promote the expansion of manufacture exports was implemented, and the industrial sector maintained its participation in the economy but with a very unstable evolution. The liberalization process became intense in the 1990s, when the manufacturing sector drastically reduced its contribution to the economy. Some authors identify this process as a deindustrialization period (Bértola and Bittencourt, 2005). Although the economy recovered its dynamism, it went through new deep crises (followed by recoveries) such as those at the beginning of the 1980s and the 2000s.

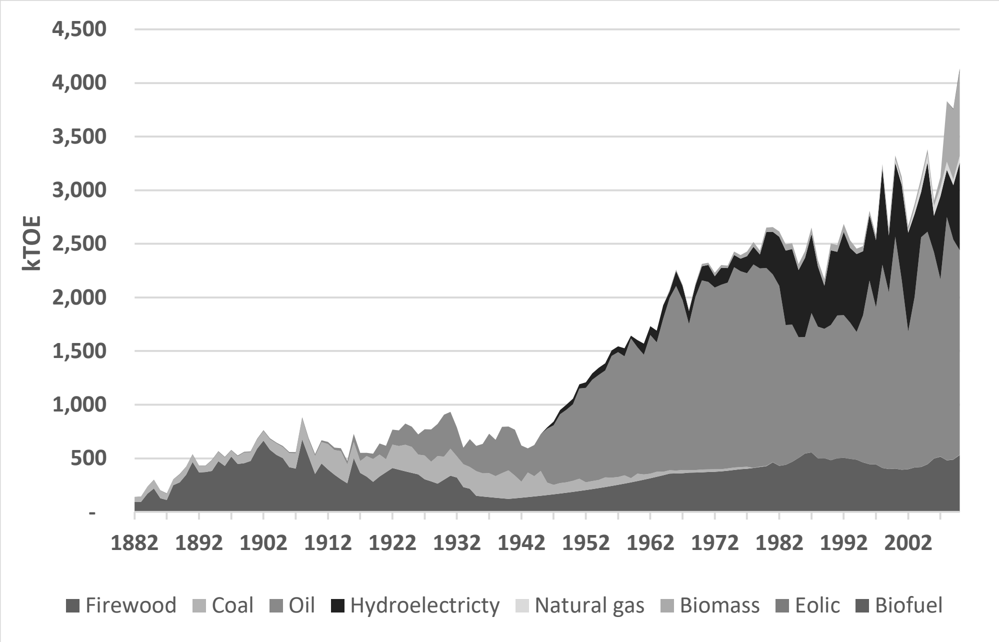
Figure 2: Uruguayan productive structure: value added by activity (% of total value added), 1882-2010.



Source: Own elaboration based on Bonino et al. (2012).

Uruguayan exports have been historically concentrated on primary products such as cattle and crops (Willebald and Bértola, 2013; Duque and Román, 2007). Because of this dependence on primary products and international markets, Uruguay has been deeply affected by the changes in international prices, especially the prices of commodities (Bértola, 2008). Another important issue is the high external dependence of the Uruguayan energy system, as the country lacks domestic reserves of fossil fuels. Figure 3 shows that the main feature of the energy transition has been the shift from traditional and domestic energy sources (firewood, muscle energy) to modern and external carriers (coal, oil and natural gas) (Bertoni and Román, 2013). The processes of structural change and international integration have driven changes in the uses of energy, like the introduction and diffusion of the railways in the late 19th and early 20th century, and the development of industrial activities and the technical systems associated with electricity demanding fossil energy during the first half of the 20th century (Bertoni and Román 2013). Coal was the main fossil fuel until the 1920s–1930s, when it was replaced by oil in a persistent but not linear process. Hydro-electricity appeared in the second half of the 20th century and although it increased its share in the energy matrix, it did not overtake oil as the most important fuel of the economy.

Figure 3: Uruguay sources of primary energy supply (kTOE), 1882-2010.



Source: Own elaboration based on Bertoni (2011) for 1882–1964, and DNE (several years) for 1965–2010.

The dynamic changes in the economic structure and its international integration have driven changes in the uses of energy. The increase in the share of industrial activity is expected to be positively related to an increase in emissions over time. Industry was promoted jointly, first with the introduction of coal (replacing firewood), and then oil (replacing coal) as the principal energy sources. This sector is much more energy intensive than other areas. In this way, any increase in the industrial share would mean more emissions because of the energy use. The decades of greater openness in Uruguay were periods of specialization in the exports driven by low-polluting activities, such as agrarian products, in response to favorable international contexts, and the share of manufacturing did not increase. On the contrary, the manufacturing sector either maintained its participation (during the First Globalization) or reduced its relative importance (since the 1980s). Therefore, the degree of openness is expected to be inversely related to CO_2 emissions, when all other things are equal.

3. Model specification and empirical strategy

The relationship between income per capita and environmental pressure or degradation can be driven by different underlying factors. This relationship is usually represented by a reduced-form model that could arise from different structural models and be the result of multiple determinants and relationships, and could also vary across countries and pollutants (Opschoor, 1995; Perman and Stern, 1999). A reduced-form model allows to understand the whole relationship between the variables of interest, exploiting the dependent variable drivers' variability. A similar approach has been employed in a wide body of literature in the estimation of the relationship between economic activity level and CO_2 emissions, allowing to obtain comparable results. This is in fact an analysis of the apparent relationship between environmental degradation and economic activity. In line with previous works, the reduced-form model relates CO_2 emissions to economic activity level (which can follow a lineal, exponential, level-log, or a quadratic functional form):

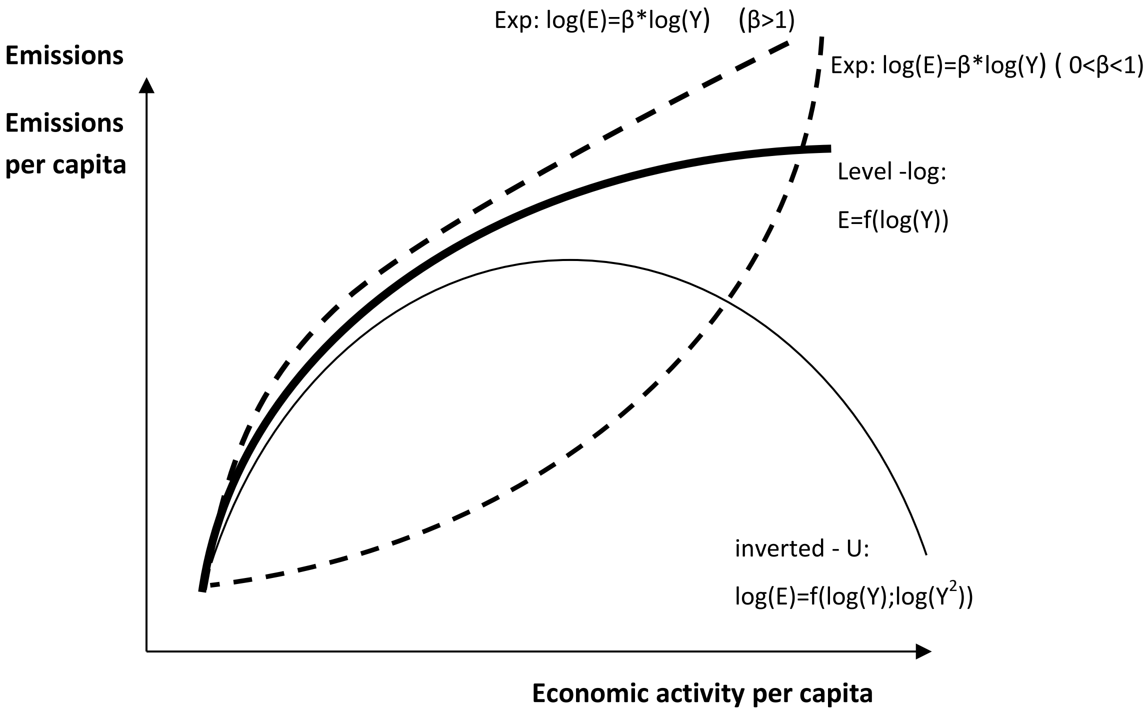
(1) $E_t = \alpha_i + \beta_1 Y_t + \beta_2 Y_t^2 + \varepsilon_t$

where E_t denotes CO_2 emissions, Y_t is income per capita in period $t=1, ...T$, and ε_t is the error term normally distributed. The correct functional form can be specified from the equation above. An inverted-U relationship is denoted by $\beta_1>0$, $\beta_2<0$.

There are no insights that determine, a priori, the functional form between carbon dioxide emissions and economic activity. Usually both variables are taken in natural logarithms, assuming that CO_2 emissions increase at a constant rate when economic activity increases. This can follow different paths depending on the magnitude of the coefficient (Figure 4). The log-log transformation is a good approach to model series variation rates, and thus the estimated parameters can be interpreted as elasticities. This allows stabilization of the data variance, and amendments to the existence of positive symmetry in the data. However, this transformation must be supported in theoretical assumptions, and must be empirically tested. This step is usually skipped in the literature that considers the relationship between the environment and economic activity; however, this is important because this relationship can follow different paths that would be omitted when automatically employing this transformation. For our purpose, three specifications are of interest (Figure 4). We employ natural logarithms for an exponential (linear in the parameters once a log-log transformation is employed) and an inverted-U specification, represented by a dashed and a continuous line, respectively, in Figure 4. The first depicts a constantly growing relationship between both variables, where the increase in emissions depends on the level of economic activity. The second one means that there is a threshold from which, once crossed, emissions start to decrease with economic activity increases. However, it may be the case that the threshold is not reached by countries, but that the increase in emissions per unit of output can decrease. This would be better reflected by a level - log functional form (as displayed by the bold line in Figure 4). This can be estimated just by applying the natural logarithms transformation to the explanatory variables, but the interpretation of the coefficients is different to that in the case of the log - log specification. While in the log - log specifications the beta parameters are interpreted as elasticities (a 1% change in Y means a β% change in E), in the level - log specification a 1% change in Y means a $\beta/100$ units change in E.

The model in Eq. (1) is extended for explaining the path of the relationship between CO_2 emissions and economic activity level. First, the composition effect has been often approached by the inclusion of the share of the industrial sector in total output (Panayoutou, 1997; Shen, 2006; Piaggio, 2008) or the share of the tertiary sector (Friedl and Getzner, 2003). The industrial sector is usually associated with higher emissions than the primary and tertiary sectors because of its higher energy intensity. In this way, it is expected that the emissions per unit of output decrease when the structure of the economies change from industry to services. We explain the composition effect using two alternative indicators: the share of the industrial sectors in economic activity and a structural composition index. Secondly, we include a measure that approaches the degree of openness of the economy (the ratio between the sum of exports and imports over total economic activity), as in previous literature (Grossman and Krueger, 1991; Cole et al., 1997; Friedl and Getzner, 2003; Piaggio, 2008; Haciloglu, 2009; Leitão, 2010; He and Wang, 2012; Shahbaz et al. 2017). The technological effect is captured, allowing a linear trend in the data (Panayoutou, 1997) —though this may also capture the effects of other variables related with time— and the share of different energy sources (Roca et al., 2001; Iwata et al., 2010).

Figure 4: Functional forms



Finally, Arrow et al. (1995) criticized the first approaches in the estimation of this relationship for ignoring the feedback between the variables. Because of this possibility, we study the relationship between CO_2 emissions and economic activity through a multi-equation model, allowing the variables to be endogenous. This means that not only can CO_2 emissions be explained by the economic activity level, but that the relationship could also be in the other direction. When the emissions are mainly a consequence of the energy consumption of productive activities, they turn into an input for income generation (Barassi and Spagnolo, 2012), though there are conflicting results on the existence or the direction of causality between economic growth and energy consumption (Ozturk, 2010). In this way, environmental policies simply restricting the use of energy could represent a constraint for the economy. Empirical works approach the feedback through Granger causality tests (Coondoo and Dinda, 2002; Dinda and Condoo, 2006; Dedeoğlu and Kaya, 2013), simultaneous equations (Hung and Shawn, 2004; Shen, 2006; Omri, 2013) and vector-autoregressive (VAR) or vector error correction models (VECM) (Piaggio, 2008; Halicioglu, 2009; Barassi and Spagnolo, 2012; Esteve and

Tamarit, 2012b; Vaona, 2012; Borozan, 2013; Septhon and Mann, 2013; Rodríguez-Caballero and Ventosa-Santaulària 2016; Shahbaz et al. 2017). Stern and Enflo (2013) employ several of the techniques at the same time.

In this paper, we estimate a VECM (Banerjee et al., 1993), which allows an estimate of the long-term relationship between non-stationary series, and their short-term relationships. Early works in the analysis of the relationship between environmental degradation and economic activity ignored the stationarity properties of the series (Carson and Mccubbin, 1997; Cole et al. 1997; and de Bruyn et al., 1998). Because CO_2 emissions and economic activity use to be non-stationary series (their parameters are not constant over time) this could have led to the estimation of spurious relations, and therefore, the estimation of a long-term relationship employing the variables in levels —without any stationary transformation— would result in non-robust estimators (meaning it would not be possible to apply inference tests) unless the series were cointegrated (Enders, 2004).

We first study the stationary properties of the series through the Augmented Dickey-Fuller unit root test (Dickey and Fuller, 1981). This determines which series are stationary and which are not. The non-stationary series are included as endogenous variables in the cointegration relationship, while the stationary ones are included as explanatory variables in the short-term relationship. Cointegration is tested using a multi-equation model as proposed by Johansen (1991). The VECM is defined departing from a vector of endogenous variables X_i, where $i=1...N$ denotes each of the variables included:

(2) $$\Delta X_{it} = A_1 \Delta X_{it-1} + ... + A_k \Delta X_{it-k} + \Pi X_{it-k} + \mu + \Gamma_1 Z_t + \Gamma_2 D_t + \varepsilon_t \quad t = 1,...,T$$

Where $\varepsilon_t \sim N(0, \sigma^2)$, μ is a constant vector, and Z_t is a vector containing exogenous variables. Finally, there are sometimes big changes in the data explained by extraordinary events. As a result, D_t, a vector that contains dummy variables, is included so as to conduct an intervention analysis until the joint residuals of the model become normally distributed (Hendry and Juselius, 2000). Intervention analysis allows to control for structural breaks that could lead to misleading results. This allows valid inference tests on the parameters.[2]

The information about the long-term relationship is contained in matrix $\Pi = \alpha\beta$, where β is the vector of coefficients of the existing long-term relationships, and α is the vector of coefficients of the long-term adjustment mechanism. After the cointegration analysis is developed, exclusion tests are conducted (significance test on the β parameters). This allows tests of which variable takes part in the long-term relationship. If a non-stationary variable is not significant in the long-term relationship, a stationary transformation of it can be included as an exogenous variable explaining the short-term dynamics. Weak exogeneity tests are conducted over the α

[2] A VECM with *n* endogenous variables provides a measure of the normality of the residuals for each of the *n* single equations, as well as a measure for the whole model. When a quadratic transformation of the economic activity level is included, the behavior of the residuals corresponding to this equation is ignored. We only check the normality of *n-1* remaining equations, as well as the normality of the model as a whole. Explaining this variable is not of interest at all, and it is only included because the VECM specification. In this way, although the joint normality test may be rejected, we make sure that it is not rejected for the other equations taken alone.

parameters to check which variables adjust to the deviations from the long term relationship. Both tests are conducted using likelihood ratio statistics between the restricted and non-restricted models. After the long-term relationship is analyzed, the short-term dynamics of the endogenous variables are studied looking at the A_i of Eq. (2).

4. Data and sources

The time series covers the period 1882–2010 as the available energy data starts in 1882. As a measure of real income per capita, we use the gross domestic product (GDP) at constant prices expressed in US dollars of 2005. The data of GDP is taken from Bonino et al. (2012) which in turn used information from the official System of National Accounts (SNA) from 1955 and historical estimations computed by Bertino and Tajam (1999) and Bértola et al. (1998). The sources of exchange rates are Bonino et al. (2015), Officer (2014), Maubrigades (2003), Vaz (1984), and Banco Central del Uruguay (data on line). The population figures for 1937–2010 are from *Instituto Nacional de Estadística* (INE) and in order to go back to 1879 we used the historical databases from the *Facultad de Ciencias Sociales*. The industrial share in economic activity is calculated as the contribution of the manufacturing and construction sectors in GDP (both variables originally expressed in pesos at current prices). This ratio is obtained from Bonino et al. (2012) which used the same sources as those described for the GDP. The Structural Composition Indicator (SCI) was constructed by Bonino et al. (2013) and consists of a synthetic indicator that depicts the transformation in the productive structure.[3] This indicator is a coefficient between 0 and 1, where 0 corresponds to the absence of structural change and values higher than 0 show evidence of changes in the productive structure. The reference for the index is the productive structure of 1870, which was mainly a primary economy. The openness coefficient is the ratio of exports plus imports to GDP (all variables in Uruguayan pesos at current prices). Trade series were calculated by Román (2016) based on SNC since 1955, and information for the previous period is restricted to goods trade and was obtained from Bonino et al. (2015), Finch (1980) and Acevedo (1933, 1934).

In the case of the Uruguayan economy, CO_2 is generated by the fossil fuel consumption of two main energy carriers: coal and oil. In order to estimate the quantity of CO_2 annually generated, first, all energy is expressed in joules and, second, emission factors by fuel type were applied. In the case of oil, 74 grams of CO_2 are emitted for every mega joule (MJ) used and the emission factor for coal is 92 grams of CO_2 per MJ. The long-term series of coal and oil were obtained from Bertoni and Román (2013). These figures were also employed to estimate the share of clean sources in the energy supply.

5. Results

[3] Bonino et al. (2013) compute the Structural Composition Indicator (SCI), following the application of Vikström (2001), for Uruguay over the period 1870–2011. This indicator is based on trigonometric notions, which combine annual data for seven sectors: Agriculture, Manufacturing, Construction, Utilities (Electricity, Gas and Water), Transport and Communications, Government, and a residual that included the other activities. The data for their calculations is the sectorial value-added time-series from Bonino et al. (2012).

We consider four variations of the environmental pressure variable: CO_2, CO_2 *per capita*, *ln*(CO_2), and *ln*(CO_2 *per capita*). The vector of endogenous variables in Eq. (4) is defined by $X_t = \{E_t, ln(GDP\ per\ capita)_t, Productive\ structure_t, Opennes\ coefficient\ _t\}$, where *Productive structure* is measured by two different indicators: *Industry share in GDP* and *Structural composition indicator*. We also tested the share of the services in total output as an indicator of the productive structure. *Share clean* is considered as exogenous, only related to the first difference of the endogenous variables. A quadratic transformation of economic activity is also included in the model for testing the inverted-U shape.

The unit root test was conducted for all the series, allowing a maximum of 4 lags (this is an extraordinarily long length when working with annual data). The results show that all the series are non-stationary (Table A1 in the Appendix), however, the *Share clean* variable (the share of clean sources in total energy supply) is non-stationary because it shows a structural break during 1900–1940, with neither a trend or a big variation in its variance. We therefore, treat this variable as stationary with a structural break, being its first difference stationary both in mean and in variance.

Looking in detail at the unit root series, all are also non-stationary in the presence of a significant linear trend. As a result, Eq. (3) is specified under the assumption of an unrestricted constant term in the autoregressive vector but no linear trends in the cointegration relationship (denoted as case 3 in Hendry and Juselius, 2000). This is consistent with the presence of a linear trend in the long-term relationship that affects both CO_2 emissions and economic activity level, but these trends cancel when included in the cointegration relationship (Hendry and Juselius, 2000). This linear trend in the cointegration relationship has been interpreted as technological progress (Mazzanti and Musolesi, 2011). There is no reason to allow a linear trend in the short-term relationship because it would not be plausible for first differences of CO_2 emissions and GDP per capita (it is very difficult to justify that growth rates constantly increase over time). We only allow one lag in the short term dynamic (*t*=1), because we are working with annual data, and allowing more lags will cause difficulties in their plausibility and interpretation. Given these assumptions, the estimated model is formally defined as:

$$(3)\ \left\{\begin{matrix} \Delta E_t \\ \Delta ln(GDP\ per\ capita)_t \\ \Delta Productive\ structure_t \\ \Delta Open\ _t \end{matrix}\right\} = A_1 \left\{\begin{matrix} \Delta E_{t-1} \\ \Delta ln(GDP\ per\ capita)_{t-1} \\ \Delta Productive\ structure_{t-1} \\ \Delta Open\ _{t-1} \end{matrix}\right\} + \Pi \left\{\begin{matrix} E_t \\ ln(GDP\ per\ capita)_t \\ Productive\ structure_t \\ Openess\ coefficient\ _t \end{matrix}\right\} + \mu + \Gamma_1 share\ clean_t + \Gamma_2 d_t + \varepsilon_t$$

Table 1 summarizes the main results for the long-term relationship. This is the elements of matrix Π in Eq. (3). We inverted the sign of the coefficients to show a more intuitive interpretation to the reader. We found that the relationship between CO_2 emissions (in per capita and absolute terms) and economic activity per capita can be explained by a level-log functional form and by a linear functional form with a log-log specification of the variables (which is equivalent to an exponential relationship between the non-transformed variables). In both cases, an increase in the share of the industrial sector in total GDP is positively correlated with CO_2 emissions, a consequence of the greater energy intensity of these sectors. The same relationship is obtained when the structural composition indicator (SCI) is used as a measure of the modifications in the productive structure. The evolution of this coefficient brings evidence of changes in the productive structure, taking as a reference the productive structure of 1870, which was mainly agrarian. Therefore, an increase in this coefficient can be understood as an industrialization process. This result is in line with Shen (2006) for China, and also Friedl and Getzner (2003), who found a positive coefficient in emissions for the share of services sectors in GDP (that is complementary to the industrial share in GDP) for Austria. This variable was not significant in Piaggio (2008) for the period 1950–2000 for Uruguay. Panayoutou (1997) and Leitão (2010) found a similar result for several countries in reference to sulfur dioxide emissions.[4]

The degree of openness of the economy is inversely related to CO_2 emissions from energy. This is explained because the periods when the Uruguayan economy openness increases are based on primary product specialization and exports. These products have low CO_2 emissions intensity. A similar result for the impact of the degree of openness in CO_2 emissions was found by Friedl and Getzner (2003) in Austria, with a negative coefficient for the ratio of imports over GDP, and Piaggio (2008) for the degree of openness in Uruguay during a shorter period. The results are also consistent with Grossman and Krueger (1991) and Leitão (2010) in reference to sulfur dioxide emissions in a panel of 42 and 94 countries respectively. The opposite result was estimated for Turkey and China by Haciloglu (2009) and by He and Wang (2012), respectively. This can be explained because both countries show economic openness processes based on industry.

The magnitude of the coefficients is much larger than the one estimated for Uruguay by Piaggio (2008), as well as for other panel or individual country studies for much shorter periods (e.g. Piaggio and Padilla 2012, Halicioglu, 2009; Barassi and Spagnolo, 2012; Esteve and Tamarit, 2012b; Vaona, 2012; Borozan, 2013; Septhon and Mann, 2013; Rodríguez-Caballero and Ventosa-Santaulària 2016; Shahbaz et al. 2017). This result may be explained by the presence of high correlation between the explanatory variables, mostly between GDP and the share of the industrial sector in total output. Multicollinearity typically has little effect on the prediction accuracy, as a reflection of the fact that the ‘total impact’ of all explanatory variables is accurately identified (Verbeek 2004). As a consequence, the models including all relevant variables in this paper can be mostly used for prediction of the relationship between carbon dioxide emissions and GDP.

[4] The inclusion of the share of the services in GDP as indicative of the productive structure shows results that are not robust and suggest a misspecification of the model. We do not show these results here for the sake of saving space, but they can be requested to the authors.

Table 1: Long-term relationship VECM

	Extensive							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	CO_2	*CO_2*	*CO_2*	*CO_2*	*$ln(CO_2)$*	*$ln(CO_2)$*	*$ln(CO_2)$*	*$ln(CO_2)$*
ln(GDP per capita)	2.06E+07 ***	7.94E+06 ***	4.12E+07 **	1.21E+07 ***	4.43 ***	4.68 ***	9.14 ***	4.58 ***
s.d.	*5.37E+06*	*1.30E+06*	*5.61E+06*	*3.13E+06*	*1.25*	*0.94*	*1.55*	*0.96*
% Manufacturing in GDP		2.79E+07 ***	7.46E+07 *			16.20 *	23.84 **	
s.d.		*0.00*	*3.00E+07*			*5.32*	*8.29*	
SCI				2.87E+07 *				8.61 *
s.d.				*6592258*				*2.07*
Openness coefficient			-9.16E+07 *	-6.01E+07 ***			-20.09 ***	-15.21 ***
s.d.			*2.02E+07*	*1.29E+07*			*5.47*	*3.70*
constant	1.17E+08	4.12E+07	2.43E+08	7.91E+07	38.87	37.10	66.27	41.69
nº observations	128	128	128	128	128	128	128	128
Joint Akaike IC	26.32	20.69	16.37	17.62	-2.48	-8.49	-13.04	-11.46
Joint Schwarz criterion	27.57	22.49	18.95	20.29	-1.86	-7.15	-10.46	-9.06
Jarque-Bera joint normality test	8.20	10.14	10.39	12.08	10.45	15.048	13.70	11.32
p-value	*0.08*	*0.12*	*0.24*	*0.148*	*0.034*	*0.0199*	*0.09*	*0.18*
Johansen cointegration test								
Cointegrating equations at 0.05 level — Trace statistic	1	1	1	1	1	1	1	1
Cointegrating equations at 0.05 level — Max-Eigenvalue statistic	1	1	1	1	1	1	1	1

Notes: ***,**,* significant at 1%, 5% and 10% respectively. VECM specification with linear trend in the cointegration relationship and 1 lag.

	Intensive							
	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	CO_2 per capita	***CO_2 per capita***	***CO_2 per capita***	***CO_2 per capita***	***ln(CO_2 per capita)***	***ln(CO_2 per capita)***	***ln(CO_2 per capita)***	***ln(CO_2 per capita)***
ln(GDP per capita)	4.86 ***	2.98 ***	12.80 ***	2.81 ***	4.11 ***	3.00 ***	6.45 ***	2.75 ***
s.d.	*1.20*	*0.58*	*1.798603*	*8.17E-01*	*1.05*	*0.57*	*0.90*	*5.73E-01*
% Manufacturing in GDP		8.55 *	25.45 **			8.83 *	16.25 **	
s.d.		*0.00*	*9.53E+00*			*3.22*	*4.80*	
SCI				6.91 **				4.63 *
s.d.				*1.7006*				*1.22E+00*
Openness coefficient			-32.79 ***	-15.94 ***			-15.00 ***	-10.31 ***
s.d.			*6.75E+00*	*3.1667*			*3.25*	*2.25E+00*
constant	27.99	15.96248	76.71	19.36	22.69	8.83	36.94	16.88
nº observations	128	128	128	128	128	128	128	128
Joint Akaike IC	-2.55	-8.35	-12.60	-11.64	-2.98	-8.596371	-12.93	-11.86
Joint Schwarz criterion	-1.79	-7.01	-10.64	-9.14	-2.00	-7.192637	-10.35	-8.92
Jarque-Bera joint normality test	5.76	13.3322	12.85	6.87	11.74	12.57157	15.43	9.33
p-value	*0.217*	*0.0381*	*0.12*	*0.551*	*0.019*	*0.0504*	*0.0514*	*0.31*
Johansen cointegration test								
Cointegrating equations at 0.05 level — Trace statistic	1	1	1	1	1	1	1	1
Cointegrating equations at 0.05 level — Max-Eigenvalue statistic	1	1	1	1	1	1	1	1

Notes: ***,**,* significant at 1%, 5% and 10% respectively. VECM specification with linear trend in the cointegration relationship and 1 lag.

We had very similar results when working with and without the natural logarithm transformation of CO_2 emissions. For testing the best functional form, we conducted uni-equation models where an adjusted transformation of CO_2 emissions in levels and logarithms is regressed against $ln(GDP\ per\ capita)$. In order to compare the goodness of fit of a model in which the dependent variable is in logs with a model in which the dependent variable is in levels, an adjusted model must be constructed, because the residual sum square (RSS) is not comparable between both models. For this, CO_2 emissions are standardized, dividing them by the geometric mean (CO_2 adj). After that, the Box-Cox statistic was conducted to test the null hypothesis that both models are equal (Table 2).[5] The results show that working with the logarithm transformation of CO_2 emissions for modeling its relationship with the logarithm of GDP per capita gives very similar results as when not employing it. This means that if the slope of this relationship decreases over time as is the case in a level - log functional form (see Figure 4), this change is so small that it can be similarly approached using a linear model. In the VECM above we employed both transformations for checking the role of other determinants, but this result must be kept in mind when interpreting the final results.

Table 2: Uni-equation models

	CO_2 adj	***ln(CO_2 adj)***	***CO_2 per capita adj***	***ln(CO_2 per capita adj)***
ln(GDP per capita)	1.62 *	1.02 *	0.60 *	0.51 *
s.d.	*2.21*	*2.21*	*0.13*	*0.14*
cte.	-11.83 *	-8.43 *	-3.85	-4.20 *
s.d.	*0.27*	*0.27*	*1.12*	*1.15*
RSS	151.12	150.13	38.85	41.0
N	132	132	132	132
Box-Cox	0.431		3.60	

Note: *, **, *** significant at 1%, 5% and 10% respectively.

The quadratic term of the economic activity level is significant but always depicts a U-shaped relationship (Table A2 in the Appendix), contrary to the expected result, which would be difficult to interpret in economic terms. When including the quadratic variable, the other determinants lose significance or show the opposite sign to the one that is expected. This means that including the quadratic term just brings distortion to the model, and should not be considered. In this way, an inverted U-shaped functional form is also discarded.[6]

[5] The Box-Cox statistic is equal to N/2*log(RSSlargest/RSSsmallest) ~ $\chi_2(1)$). If the estimated value exceeds its critical value (from tables Chi-squared at 5% level with 1 degree of freedom is 3.84) the null hypothesis that the models are the same is rejected (i.e. they are significantly different in terms of goodness of fit).

[6] It was not possible to normalize the residuals of models (12) and (16) in Table A2 and A3 without an extremely large number of interventions, however, considering the results for all the other models, it is reasonable to reject the existence of an inverted U-shaped relationship for this specification too. It is also notable from Table A2 in the Appendix that when including the quadratic term of the economic activity level, a second cointegration equation appears to be significant in some cases. This is because even though the Johansen cointegration test (Johansen, 1991) is the most robust methodology for cointegration testing, it becomes problematic when a non-linear transformation of the variables already present is included. Similar results have been shown by Haciloglu (2009). This second cointegration relationship

Table 3 shows the cointegration term (α_i) and the coefficient associated with the *Share clean* variable from Eq. (5) for those models shown in Table 1. This is, the impact of the error-correction term and the share of clean energies in the first difference of each of the endogenous variables. The cointegration term shows the right sign and is between 0 and 1 for all the variables. This means that if the series suffers a shock they turn back to the long-term relationship. This result is consistent with previous results in the literature employing multi-equation models. All the variables endogenously adjust to the estimated long-term relationship. In this way, not only are the emissions explained by the per capita economic activity level, the economic structure and the degree of openness, but the emissions also explain the deviations of these variables from the long-term relationship. The degree of openness and the structural decomposition index are weakly exogenous, however, in models (7) and (16) respectively. Because of this, we cannot be conclusive about these variables in all the cases. The fact that the degree of openness is weakly exogenous in model (7) can be explained because Uruguay is a very small country, for which trade is mainly driven by international prices, which are exogenous to the country, however, this is a particular case. The SCI measures modifications in the production composition based on information about several sectors of the economy —not just the industrial sector— which may be less closely related to energy consumption. This can explain the difference in the significance of the cointegration term between models (8) and (16). However, both variables are endogenous in seven of the eight specifications, suggesting that they adjust together with the other variables to deviations from the long-term relationship.

has been ignored, given that it is not of interest to explain the adjustments of the quadratic transformation of the per capita economic activity level.

Tables 3: Cointegration terms (CI) and *Share clean* coefficients in the short-term dynamics

Extensive								
	(1)		**(2)**		**(3)**		**(4)**	
	CO_2		***CO_2***		***CO_2***		***CO_2***	
	CI term	**d(share clean)**	**CI term**	**d(share clean)**	**CI term**	**d(share clean)**	**CI term**	**d(share clean)**
d(CO_2)	-0.0062	-2412959.0 ***	-1.47E-02 *	-2536443 ***	-0.0031 ***	-2470269.0 ***	-0.0112 ***	-2594981.4 ***
s.d	*0.0034*	*480994.00*	*0.0093*	*520121*	*0.0019*	*529369.90*	*0.0044*	*495921.03*
d(ln(GDP per capita))	5.31E-09 ***	0.096	1.48E-08 ***	0.0465	4.50E-09 *	0.0549	5.87E-09 ***	0.1751
s.d	*0.0000*	*0.249*	*4.60E-09*	*0.2596*	*0.0000*	*0.2434*	*0.0000*	*0.2415*
d(% Manufacturing in GDP)			1.53E-09 ***	0.0261	1.66E-10 ***	0.0063		
s.d			*4.90E-10*	*0.0273*	*0.0000*	*0.0249*		
d(SCI)							9.13E-10 **	0.0987 **
s.d							*0.0000*	*0.0491*
d(Openness coefficient)					-6.81E-10 *	-0.0138	-1.74E-09 ***	-0.0544
s.d					*0.0000*	*0.0730*	*0.0000*	*0.0664*
Lags	1		1		1		1	
	1		1		1		1	
Interventions – Scale	2002 2004 1983 1938 1931 1934 1960 1921 1920 1979 1885 1982		2002 2004 1983 1938 1931 1934 1960 1921 1920 1979 1885		2002 2004 1983 1938 1931 1934 1960 1979 1885 1905 1921 1920		2002 2004 2006 2008 1983 1931 1892 1960 1920 1958	
Interventions – Shock	1972 1965 2007 2000 1996 1998 2005 2008 1968 1987		1972 1965 2007 2005 2000 1996 1998 2008 1987		1972 1965 2007 2000 1996 1998 2005 1968 1911		1996 1998 2000 1972 1965 1938 1921 1894 1933 1968 1944 1889	
Notes: ***,**,* significant at 1%, 5% and 10% respectively. VECM specification with linear trend in the cointegration relationship and 1 lag.								

Extensive									
		(5)		(6)		(7)		(8)	
		ln(CO2)		ln(CO2)		ln(CO2)		ln(CO2)	
		CI term	d(share clean)	CI term	d(share clean)	CI term	d(share clean)	CI term	d(share clean)
d(lnCO_2)		-0.0123 *	-1.7761 ***	-0.0098 *	-1.94 ***	-0.0062 **	-1.8413 ***	-0.0112 **	-1.8463 ***
s.d		*0.0074*	*0.2446*	*0.0064*	*0.2175*	*0.0032*	*0.1957*	*0.0059*	*-0.2006*
d(ln(GDP per capita))		0.0224 ***	-0.0316	0.0178 **	0.02	0.0128 ***	0.1683	0.0259 ***	0.0517
s.d		*0.0070*	*0.2335*	*0.0073*	*0.2494*	*0.0037*	*0.2240*	*0.0070*	*-0.2383*
d(% Manufacturing in GDP)				0.0020 **	-0.0023	0.0010 **	-0.0019		
s.d				*0.0008*	*0.0271*	*0.0004*	*0.0264*		
d(SCI)								0.0025 *	0.0965 **
s.d								*0.0015*	*-0.0507*
d(Openness coefficient)						-0.0013	-0.1663 ***	-0.0034 *	-0.1525 **
s.d						*0.0012*	*0.0708*	*0.0020*	*-0.0679*
Lags		1		1		1		1	
		1		1		1		1	
Interventions	Scale	1931 2002 1983 1934 1958		1931 2002 1983 1979 1934 1894 1884 1958		1931 2002 1983 1934 1884 1979 1960 1958 1894 1920 1982 1915		1931 2002 1983 1892 1960 1934 1884 1920 2008	
	Shock	1972 1965 1938		1972 1965 1938 1885 1908		1972 1965 1938 1921 1908 1885 1916 1998 1897		1972 1965 1938 1921 1894 1915 1917 1908 1885 1998	

Notes: ***,**,* significant at 1%, 5% and 10% respectively. VECM specification with linear trend in the cointegration relationship and 1 lag.

Intensive								
	(9)		**(10)**		**(11)**		**(12)**	
	CO2 *per capita*		**CO2 *per capita***		**CO2 *per capita***		**CO2 *per capita***	
	CI term	**d(share clean)**	**CI term**	**d(share clean)**	**CI term**	**d(share clean)**	**CI term**	**d(share clean)**
d(CO_2 per capita)	-0.0155 ***	-0.2 ***	-0.0180 *	-1.6933 ***	-0.0043 *	-1.5435 ***	-0.0161 **	-1.2694 ***
s.d	*-0.0080*	*-0.07*	*0.0117*	*0.2502*	*0.0028*	*0.2366*	*0.0078*	*0.2311*
d(ln(GDP per capita))	2.24E-02 *	-0.058	0.0323 ***	0.0188	0.0135 ***	-0.0128	0.0229 ***	-0.1668
s.d	*-0.0073*	*-0.068*	*0.0112*	*0.2397*	*0.0026*	*0.2238*	*0.0082*	*0.2456*
d(% Manufacturing in GDP)			0.0035 ***	0.0196	0.0006 **	0.0186		
s.d			*0.0012*	*0.0266*	*0.0003*	*0.0269*		
d(SCI)							0.0032 *	0.0695
s.d							*0.0018*	*0.0534*
d(Openness coefficient)					-0.0024 ***	-0.0378	-0.0064 ***	-0.0229
s.d					*0.0008*	*0.0662*	*0.0022*	*0.0661*
Lags	1		1		1		1	
	1		1		1		1	
Interventions – Scale	1938 1931 1983 1934 2002 1982 1921 1920 2008 1999		1938 1931 1983 2002 1960 1934 1921 1979 1920 2004		1938 1931 1983 1960 1979 2002 1934 1921 2008 1920 2004		1892 2008 2004 1960 1982 1958 1920	
Interventions – Shock	1972 1965		1972 1965 2005		1972 1965 1998		1972 1965 1938 1931 1894 1982 1921 2000 1998 2002 1933 1944 1887	

Notes: ***,**,* significant at 1%, 5% and 10% respectively. VECM specification with linear trend in the cointegration relationship and 1 lag.

Intensive								
	(13)		(14)		(15)		(16)	
	ln(CO2 *per capita*)		ln(CO2 *per capita*)		ln(CO2 *per capita*)		ln(CO2 *per capita*)	
	CI term	d(share clean)	CI term	d(share clean)	CI term	d(share clean)	CI term	d(share clean)
d(lnCO$_2$ per capita)	-0.0133	-2.2629 ***	-0.0168 *	-1.8712 ***	-0.0079 *	-1.9729 ***	-0.0157 *	-1.9797 ***
s.d	*0.0065*	*0.2013*	*0.0106*	*0.2311*	*0.0050*	*0.2179*	*0.0089*	*0.2039*
d(ln(GDP per capita))	0.0245 ***	-0.0957	0.0331 ***	-0.1318	0.0236 ***	0.0991	0.0413 ***	-0.0162
s.d	*0.0084*	*0.2586*	*0.0107*	*0.2320*	*0.0050*	*0.2183*	*0.0097*	*0.2224*
d(% Manufacturing in GDP)			0.0029 ***	0.0074	0.0013 **	-0.0065		
s.d			*0.0011*	*0.0247*	*0.0006*	*0.0271*		
d(SCI)							0.00236	0.075535
s.d							0.00239	0.05484
d(Openness coefficient)					-0.0044 ***	-0.0506	-0.0094 ***	-0.0389
s.d					*0.0017*	*0.0746*	*0.0034*	*0.0783*
Lags	1		1		1		1	
	1		1		1		1	
Interventions — Scale	1931 1983 1934 1958 1886 1884 2002 1894 1915		1938 1931 1983 1934 1920 1979 2002 1958 1894 1884		1938 1931 2002 1934 1979 1921 1894 1958 2004 1884 1920 1983 1982 1915		1938 1931 1892 1982 1983 2004 2002 1921 1920 1958 1884 1915 2008	
Interventions — Shock	1972 1965 1938 1908 1998 1916 1887		1972 1965 1885 1959		1972 1965 1959 1908 1885 1998 1916		1972 1965 1894 1959 1887 1908 1916 1885 1933 1889 1998 1899	
Notes: ***,**,* significant at 1%, 5% and 10% respectively. VECM specification with linear trend in the cointegration relationship and 1 lag.								

Finally, the *Share clean* variable is always significant for explaining the variations in CO_2 emissions from energy consumption (both in levels and per capita), with a negative parameter. This explains that increases in the share of clean sources of energy in the Uruguayan energy matrix substitute, at least partially, for polluting sources instead of increasing the total energy supply.

6. Discussion and conclusions

This paper analyses the relationship between CO_2 emissions from fossil fuels consumption and per capita economic activity level in Uruguay during the period 1882–2010. This is an extraordinary time span for the analysis of a developing country, which allows identification of a real long-term relationship. The evidence for developing countries is scarce and a long-run perspective helps to improve our knowledge of these economies and its specificities. The paper contributes to the literature showing evidence for a small open economy of a developing country, which besides its specific interest, can also be extrapolated to understand the case of similar countries. We explore several functional forms, something that is usually missed in the literature, allowing the relationship to be logarithmic among the variables, in addition to the linear and quadratic models that are usually analyzed in parametric estimations in this field. This is very relevant, because a misspecification could lead to biased estimates. We also look at the absolute and per capita terms of pollution. Empirical exercises often estimate the relationship only in reference to per capita emissions. These works usually compare results between countries, but do not give a clear indication of the consequences of economic activity on the environmental pressure. This is because while per capita emissions may be diminishing, the absolute level of emissions can continue rising due to population growth. If this happens, the pressure on the environment will not be alleviated. This is a novelty in the literature, where the absolute level of pollution is usually missed, while is the relevant indicator when thinking about the impact on CO_2 atmospheric concentrations and resulting climate change. Other explanatory variables are included in the model in order to consider the productive structure, and the degree of openness of the economy. Finally, the feedback among the variables is tested through the estimation of a multi-equation model. This allows the variables to be treated as endogenous, also testing whether other explanatory variables adjust to the deviations from the long-term relationship.

The results show that when the log-log transformation is employed there is a linear long-term relationship between CO_2 emissions from fossil fuels consumption and GDP per capita in Uruguay between 1882 and 2010 (which would involve an exponential relationship between the original non-transformed variables). If the relationship is approached by a level-log specification, the results are very similar to the linear log-log specification. In this way, even though a level-log relationship is plausible, the degree to which the slope of the relationship between emissions and GDP per capita decreases is so small that the results are non-statistically different. The existence of an inverted-U shaped curve is rejected, as the coefficient of the quadratic variable shows the contrary sign to the one expected and distorts the model. Moreover, the magnitude of the coefficients is larger than the once estimated for Uruguay by Piaggio (2008) and other panel or individual country studies for much shorter periods. This is as a result of the presence of high correlation between the explanatory variables. As a consequence, the models including all significant variables in this paper can be mostly used for prediction of the relationship between carbon dioxide and GDP, given that multicollinearity typically has little impact on the prediction accuracy, as a reflection of the fact that the 'total impact' of all explanatory variables is accurately identified (Verbeek 2004).

Neither absolute nor per capita emissions of Uruguay diminished with GDP per capita growth, however, over this long period the country exhibits a very low per capita economic growth (1.3% cumulative annual growth rate). However, we cannot reject the level-log model, we cannot reject the fact that emissions increase at a decreasing rate in reference to the increase in economic level activity. Moreover, Uruguayan per capita economic activity levels barely exceeded the turning point computed for France by Piaggio and Padilla (2012) only for two observations in 1882–2010. France is the developed country with the lowest turning point in this study, and its inverted U-shaped path is mainly explained by an increase of nuclear energy in its energy matrix. Thus, despite the Uruguayan path being linear, this may be so because it is still at a lower developmental stage than other countries with a non-linear path.

Changes in the product structure, either measured by the industrial share in total output or by the synthetic indicator of structural change, is positively associated with CO_2 emissions. This is a consistent result in the literature, and a consequence of the composition effect, however, it is noticeable that this result emerges in a very long-term relationship, given that it was absent for a shorter period, 1950–2000, in Piaggio (2008). As was previously described, the manufacturing industry grew rapidly during the import substitution industrialization model from the 1930s until the 1950s. The industrial share recovered its levels during the 1970s and 1980s but then started a decreasing trend in the 1990s. In terms of final energy use by sector, the industrial sector was the most important consumer during the 1940s and 1950s, representing half of the total energy consumption, remaining at the same level in the following decades, however, in relative terms, it presents a decreasing trend as other sectors such as transportation and residential became more energy intensive (Bertoni, 2011). During that period, the Uruguayan energy matrix was based mostly on coal and oil, what explains the impact of the increase of energy demand on CO_2 emissions. These two issues explain the importance of the changes in the productive structure when an extended time length is considered. By the time the economy is more open, CO_2 emissions from energy consumption diminish. This is explained by the fact that the periods where the Uruguayan economy has been more open were based on primary exports (mainly livestock and agricultural products) with little importance held by industrial products, as well as the diversification of the energy matrix to cleaner sources during the same period. The structure of exports reflects the characteristics of the manufacturing sector that has been mostly composed of handicrafts, with very low installed power and labor concentration (see Willebald and Bértola (2013) for the first decades of the 20th century, and Bértola and Bittencourt (2005) for the more recent period of openness).

There is feedback between CO_2 emissions from energy consumption, per capita economic activity level and industrial share. Energy can represent a restriction in economic growth, which is reflected in this result. This means that CO_2 emissions from energy consumption would be a determinant factor of GDP growth. In this way, restrictions in the use of energy from fossil fuel sources could represent a threat to economic growth if it is not accompanied by efficiency improvements or replacing them with clean energy sources. The significance of the share of clean sources in total energy supply shows that changes in the energy matrix can result in an increase in the energy supply without increasing CO_2 emissions from energy consumption.

In summary, an increase in economic activity level alone is not a solution for decreasing Uruguayan CO_2 emissions in the long-term. Despite the country being at a lower development stage than countries that followed a non-linear path, the literature shows that if changes in primary energy sources are not explicitly encouraged, economic growth alone does not help to diminish emissions. The literature also shows that these policies help to achieve the turning point with a lower level of environmental pressure. If the country expects to develop through a productive structural change where the share of industrial sectors increases, it should be supported by energy efficiency improvements and the increase of the share of clean sources in the energy supply. In this sense, the diversification of the energy matrix by substitution with clean energies, as has been encouraged by the national government in recent years, is a smart strategy for reversing this relationship.

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Appendix

Table A1: ADF Unit Root test

Null Hypothesis: the serie has a unit root		CO_2		CO_2 per capita		$ln(CO_2)$		ln(CO2 per capita)	
		Constant	Const. + Trend	Constant	Const. + Trend	Constant	Const. + Tre	Constant	Const. + Trend
Levels	t-stat	-0.143311	-1.975031	-0.951868	-2.003635	-2.124517	-1.221656	-1.250928	-1.779413
	p-value	0.9413	0.6092	0.7686	0.5935	0.2355	0.9013	0.6508	0.7092
	Nº lags	3	3	3	3	3	3	3	3
	RU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
1st diff.	t-stat	-4.812184	-4.804116	-9.593342	-9.553825	-10.00281	-10.25593	-10.40307	-10.38673
	p-value	0.0001	0.0008	0	0	0	0	0	0
	Nº lags	4	4	2	2	2	2	2	2
	RU	No	No	No	No	No	No	No	No

		ln(GDP per capita)		% Manufactures in GDP		SCI		Openness coefficient	
		Constant	Const. + Trend	Constant	Const. + Trend	Constant	Const. + Tre	Constant	Const. + Trend
Levels	t-stat	-1.779413	-2.708376	-1.823378	-1.963725	-1.298775	-3.242065	-1.403373	-2.556589
	p-value	0.7092	0.0753	0.3679	0.6152	0.629	0.0809	0.5789	0.3009
	Nº lags	3	0	0	0	0	0	1	1
	RU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
1st diff.	t-stat	-10.38673	-11.83745	-11.22554	-11.23091	-9.484162	-9.451661	-13.97329	-14.06543
	p-value	0	0	0	0	0	0	0	0
	Nº lags	2	0	0	0	1	1	0	0
	RU	No	No	No	No	No	No	No	No

		share_clean	
		Constant	Const. + Trend
Levels	t-stat	-1.388799	-1.009779
	p-value	0.5859	0.9382
	Nº lags	0	0
	RU	Yes	Yes
1st diff.	t-stat	-9.14871	-9.244286
	p-value	0	0
	Nº lags	1	1
	RU	No	No

Table A2: VECM long term relationship quadratic model

	Extensive							
	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
	CO_2	CO_2	CO_2	CO_2	$ln(CO_2)$	$ln(CO_2)$	$ln(CO_2)$	$ln(CO_2)$
ln(GDP per capita)	4.56E+08 ***	9.35E+08 ***	2.80E+08 ***	2.06E+08 ***	318.99 ***	27.866	61.72 ***	88.23 ***
s.d.	*61218731*	*1.34E+08*	*3.69E+07*	*2.94E+07*	*91.39*	*27.2699*	*19.597*	*14.239*
ln(GDP per capita)^2	4.39E+07 ***	9.06E+07 ***	2.69E+07 ***	1.96E+07 ***	30.99 ***	2.00	5.28 ***	8.52 ***
s.d.	*5568033*	*1.22E+07*	*3.34E+06*	*2659363.37*	*8.34*	*2.49*	*1.783*	*1.290*
% Manufacturing in GDP		-3.64E+07	-2.48E+06			10.38	23.84 ***	
s.d.		*3.60E+07*	*1.02E+07*			*7.18*	*5.361*	
SCI				2.51E+06				4.78
s.d.				*3.20E+06*				*1.648*
Openness coefficient			7.46E+06	2.47E+06			-25.98 ***	-2.11
s.d.			*7.29E+06*	*5.69E+06*			*3.83*	*2.841*
constant	1.18E+09	2400000000	7.23E+08	5.37E+08	827.3	105.13	196.73	240.18
nº observations	128	128	128	128	128	128	128	128
Joint Akaike IC	23.12	17.58256	13.62	13.62	-5.15	-10.81	-15.23	-13.77
Joint Schwarz criterion	25.46	20.70197	17.18	17.18	-3.55	-7.9584	-12.11	-10.76
Jarque-Bera joint normality test	27.89	32.56081	10.18	15.40	17.53	52.493	24.23	187.63
p-value	*0.00*	*0.0001*	*0.42*	*0.12*	*0.0075*	*0.00*	*0.01*	*0.00*
Johansen cointegration test								
Cointegrating equations at 0.05 level — Trace statistic	2	2	2	1	1	1	1	1
Cointegrating equations at 0.05 level — Max-Eigenvalue statistic	2	1	2	1	1	0	1	2

Notes: ***,**,* significant at 1%, 5% and 10% respectively. VECM specification with linear trend in the cointegration relationship and 1 lag.

	Intensive							
	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)
	CO_2 per capita	***CO_2 per capita***	***CO_2 per capita***	***CO_2 per capita***	***ln(CO_2 per capita)***	***ln(CO_2 per capita)***	***ln(CO_2 per capita)***	***ln(CO_2 per capita)***
ln(GDP per capita)	202.25 ***	366.64 ***	147.45 ***	32.34	184.02 ***	284.45 ***	85.39 ***	469.92 ***
s.d.	*24.98*	*62.64*	*20.72*	*20.89*	*28.026*	*47.342*	*16.718*	*104.162*
ln(GDP per capita)^2	*19.42* ***	35.86 ***	14.32 ***	-2.65	-17.94 ***	27.97 ***	8.31 ***	46.19 ***
s.d.	*2.27*	*5.70*	*1.876*	*20.89*	*2.554*	*4.310*	*1.516*	*104.162*
% Manufacturing in GDP		-23.10	-4.44			-5.59	7.60 ***	
s.d.		*17.17*	*5.921*			*12.787*	*4.787*	
SCI				-3.76				-10.90
s.d.				*2.224*				*12.099*
Openness coefficient			1.48	25.21 ***			-2.91	9.80
s.d.			*4.453*	*4.266*			*3.744*	*21.737*
constant	523.3	932.5	377.28	104.90	467.09	715.50	216.59	1181.14
nº observations	128	128	128	128	128	128	128	128
Joint Akaike IC	-5.85	-11.05	-15.59	-14.84	-5.36	-11.15	-16.51	-14.44
Joint Schwarz criterion	-4.11	-9.00	-12.02	-9.38	-3.75	-8.75	-10.94	-10.43
Jarque-Bera joint normality test	42.18	79.11	18.74	22.93	32.40	50.50	20.53	38.04
p-value	*0.00*	*0.00*	*0.04*	*0.011*	*0.0000*	*0.0000*	*0.0246*	*0.00*
Johansen cointegration test								
Cointegrating equations at 0.05 level — Trace statistic	1	1	2	1	1	1	2	2
Max-Eigenvalue statistic	1	1	2	1	1	1	2	2

Notes: ***,**,* significant at 1%, 5% and 10% respectively. VECM specification with linear trend in the cointegration relationship and 1 lag.

Table A3: Cointegration terms and *Share clean* coefficients in the short term dynamics - quadratic model

Extensive								
	(19)		**(18)**		**(19)**		**(20)**	
	CO_2		***CO_2***		***CO_2***		***CO_2***	
	CI term	**d(share clean)**	**CI term**	**d(share clean)**	**CI term**	**d(share clean)**	**CI term**	**d(share clean)**
d(CO_2)	0.0036 **	-2.36E+06 ***	0.0017 **	-2.51E+06 ***	0.0064 **	-2.53E+06 ***	0.0091 **	-2.52E+06 ***
s.d	*0.0019*	*5.05E+05*	*0.0009*	*5.47E+05*	*0.0031*	*5.16E+05*	*0.0045*	*5.30E+05*
d(ln(GDP per capita))	-3.81E-09 ***	0.12	-1.75E-09 ***	0.11	-6.82E-09 ***	0.14	-8.39E-09 ***	0.1905
s.d	*0.0000*	*0.1990*	*0.0000*	*0.1997*	*0.0000*	*0.2293*	*0.0000*	*0.2402*
d(ln(GDP per capita)^2)	4.70E-08 ***	-1.1987	2.15E-08 ***	-1.0405	0.0000 ***	-1.4949	1.04E-07 ***	*-2.0387*
s.d	*0.0000*	*2.2180*	*0.0000*	*2.2267*	*0.0000*	*2.5447*	*0.0000*	*2.6658*
d(% Manufacturing in GDP)			-3.99E-11	0.0301	-9.46E-11	0.0272		
s.d			*0.0000*	*0.0286*	*0.0000*	*0.0276*		
d(SCI)							-4.36E-10	0.1044 **
s.d							*0.0000*	*0.0571*
d(Openness coefficient)					1.86E-09 ***	-0.0381	2.48E-09 ***	-0.0635
s.d					*0.0000*	*0.0676*	*0.0000*	*0.0681*
Lags	1		1		1		1	
	1		1		1		1	
Interventions – Scale	2002 2004 1983 1938 1931 1934 1960 1921 1920 1979 1885 2010 1958 1974 1959		2002 2004 1983 1938 1931 1934 1960 1921 1920 1979 1885 2010 1958 1982 1959 1974		1983 1938 1931 2002 2004 1934 1979 1960 1982 1921 1920 1885 2010		1938 1931 2002 2007 2004 1983 1934 1894 1892 1960 1982 2010 1920	
Interventions – Shock	1972 1965 2007 2000 1996 1998 2005 2008 1982 1968 1987 1951 1918		1972 1965 2007 2005 2000 1996 1998 2008 1987 1951 1918		1972 1965 2007 2000 1996 1998 1968 2006 1957 1958		1972 1965 2000 1996 1998 1958 1968 1921 2006 1957 1890	
Notes: ***,**,* significant at 1%, 5% and 10% respectively. VECM specification with linear trend in the cointegration relationship and 1 lag.								

Extensive									
		(21)		**(22)**		**(23)**		**(24)**	
		ln(CO2)		***ln(CO2)***		***ln(CO2)***		***ln(CO2)***	
		CI term	**d(share clean)**	**CI term**	**d(share clean)**	**CI term**	**d(share clean)**	**CI term**	**d(share clean)**
d(lnCO $_2$)		0.0023 ***	-1.77 ***	-0.0066	1.3409 **	0.0038	-1.6581 ***	0.0046	-2.0736 ***
s.d		*0.0013*	0.23113	*0.0051*	*0.6806*	*0.0056*	*0.2374*	*0.0050*	*0.2430*
d(ln(GDP per capita))		-0.003 **	0.24472	0.0170 ***	-0.5846	1.66E-02 ***	-0.0817	-0.0198 ***	-0.2265
s.d		*0.0012*	0.22528	*0.0058*	*0.7746*	*0.0049*	*0.2082*	*0.0041*	*0.1986*
d(ln(GDP per capita)^2)		0.037 *	-2.6624	-0.1916 ***	7.0050	-0.1719 ***	0.9751	0.2451 ***	2.7151
s.d		*0.0136*	2.51882	*0.0647*	*8.6956*	*0.0551*	*2.3354*	*0.0453*	*2.1968*
d(% Manufacturing in GDP)				0.0010	0.1654 *	7.69E-04	0.0218		
s.d				*0.0007*	*0.0899*	*0.0006*	*0.0268*		
d(SCI)								-0.0008	0.1355 ***
s.d								*0.0009*	*0.0453*
d(Openness coefficient)						-1.52E-03	-0.1072 *	0.0063 ***	-0.1015
s.d						*0.0015*	*0.0647*	*0.0014*	*0.0655*
Lags		1		1		1		1	
		1		1		1		1	
Interventions	Scale	1931 2002 1983 1934 1958 1982 1894 1884 1974 1915 1920				1931 2002 1979 1894 1884 1936 2006 1982 1920		1938 1931 1892 1960 2002 1934 1958 1884 1944 1890 1982 1974 1886	
	Shock	1972 1965 1938 2009 1921 1916				1972 1965 1938 1983 1960 2009 1958 1921 1933 1959 2009		1972 1965 1894 2009 1887	

Notes: ***,**,* significant at 1%, 5% and 10% respectively. VECM specification with linear trend in the cointegration relationship and 1 lag.

Intensive								
	(25)		(26)		(27)		(28)	
	CO2 *per capita*		CO2 *per capita*		CO2 *per capita*		CO2 *per capita*	
	CI term	d(share clean)	CI term	d(share clean)	CI term	d(share clean)	CI term	d(share clean)
d(CO_2 per capita)	0.0024	-1.61 ***	0.0014	-1.7213 ***	0.0036	0.9764	0.0013	-1.7214 ***
s.d	*0.0024*	*0.249*	*0.0011*	*0.2530*	*0.0026*	*0.6944*	*0.0053*	*0.2445*
d(ln(GDP per capita))	-0.0095 ***	0.11	-0.0040 ***	0.1131	-0.0126	0.4026	0.0145 ***	-0.1530
s.d	*0.0019*	*0.199*	*0.0009*	*0.1987*	*0.0023*	*0.6231*	*0.0043*	*0.2010*
d(ln(GDP per capita)^2)	0.1160 ***	-1.08	0.0490 ***	-1.0789	0.1535	-4.2169	-0.1545 ***	1.9589
s.d	*0.0209*	*2.207*	*0.0098*	*2.2048*	*0.0255*	*6.8973*	*0.0490*	*2.2714*
d(% Manufacturing in GDP)			-0.0001	0.0216	-0.0002	0.1518 **		
s.d			*0.0001*	*0.0261*	*0.0003*	*0.0837*		
d(SCI)							0.0013 *	0.0677
s.d							*0.0013*	*0.0611*
d(Openness coefficient)					0.0029	-0.0201	-0.0052 ***	0.0277
s.d					*0.0007*	*0.1941*	*0.0015*	*0.0679*
Lags	1		1		1		1	
	1		1		1		1	
Interventions – Scale	1938 1931 1983 1960 1979 2002 1934 1921 2008 1920 2004 2010 1958 1982 1959 1974		1938 1931 1983 1960 1979 2002 1934 1921 2008 1920 1958 1982		1938 1931 1983 1960 1979 2002 1934 1921 2008 1920 2004 1982 2006 1991 1959		1892 2008 2004 1960 1982 1958 1920 1974 2006 1979 1936 1948 1991 1988	
Interventions – Shock	1972 1965 1998		1972 1965 2009		1972 1965 1998 2009 1957 1885 1974 2000		1972 1965 1938 1931 1894 1982 1921 2000 1998 2002 1933 1944 1887 2009 1951 1918 1985 1941 1885 1889 1967 1905 1916 1908	
Notes: ***,**,* significant at 1%, 5% and 10% respectively. VECM specification with linear trend in the cointegration relationship and 1 lag.								

Intensive								
	(29)		(30)		(31)		(32)	
	ln(CO2 *per capita*)		ln(CO2 *per capita*)		ln(CO2 *per capita*)		ln(CO2 *per capita*)	
	CI term	**d(share clean)**	**CI term**	**d(share clean)**	**CI term**	**d(share clean)**	**CI term**	**d(share clean)**
d(lnCO$_2$ per capita)	0.0021	-1.6160 ***	0.0015	-1.7067 ***	0.0049 **	-1.7740 ***	0.0009 *	-2.0897 ***
s.d	*0.0024*	*0.2677*	*0.0014*	*0.2636*	*0.0028*	*0.1753*	*0.0006*	*0.2079*
d(ln(GDP per capita))	-0.0088 ***	0.1384	-0.0054 ***	0.1295	-0.0162 ***	0.4685 **	-0.0024 ***	0.1559
s.d	*0.0017*	*0.1949*	*0.0010*	*0.1940*	*0.0035*	*0.2162*	*0.0006*	*0.2104*
d(ln(GDP per capita)^2)	0.1087 ***	-1.3605	0.0659 ***	-1.2464	0.1984 ***	-4.9135 **	0.0302 ***	-1.4227
s.d	*0.0191*	*2.1465*	*0.0111*	*2.1431*	*0.0386*	*2.4074*	*0.0066*	*2.3252*
d(% Manufacturing in GDP)			-0.0001	-0.0006	0.0002	-0.0500 **		
s.d			*0.0001*	*0.0278*	*0.0005*	*0.0283*		
d(SCI)							-6E-06	0.080607
s.d							*0.0002*	*0.0555*
d(Openness coefficient)					0.0025 **	-0.0754	0.0006 ***	-0.0934
s.d					*0.0013*	*0.0804*	*0.0002*	*0.0726*
Lags	1		1		1		1	
	1		1		1		1	
Interventions – Scale	1938 1931 1894 1892 1982 1983 2004 1958 2002 1934 1921 1974		1938 1931 1894 1892 1982 1983 2004 1958 2002 1934 1921 1974 1979 1885		1938 1931 1892 1982 1983 2004 2002 1921 1920 1958 1884 19152008 1979 1974 1931 1932 2006 1922 1942 1953 1912		1938 1931 1892 1982 1983 2004 2002 1921 1920 1958 1884 1915 2008 1974	
Interventions – Shock	1972 1965 1959 1951 2009		1972 1965 1959 1951 2009		1972 1965 1894 1959 1887 1908 1916 1885 1933 1889 1998 1899 2009 1968 1895 1897 2000 1951 1910		1972 1965 1894 1959 1887 1908 1916 1885 1933 1889 1998 1899 2009	

Notes: ***,**,* significant at 1%, 5% and 10% respectively. VECM specification with linear trend in the cointegration relationship and 1 lag.