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Estimation and analysis of the relationship between economic development and CO_2 emissions

Estimación y análisis de la relacion entre desarrollo económico y emisiones de CO_2

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Abstract

The environmental situation is an issue that concerns the world and that must be addressed from different angles for this reason this article aims to determine the relationship between economic development and CO_2 emissions per capita, according to the premise of Kuznets. For this, an econometric model is applied with data from the year 2003-2016, for eleven (11) countries: Germany, Argentina, Australia, Brazil, Canada, Chile, China, Colombia, United States, United Arab Emirates and Russia. The results obtained from the econometric model used partially confirm the hypothetical relationship posed by the CAK environmental curve. A fuzzy logic model complements this finding where the variability of the behavior of future CO_2 emissions is appreciated according to the input variable GDP per capita and CO_2 per capita. Both models lead to a holistic, inclusive and creative understanding of the environmental situation. It is concluded from the data used for the two models of increase or decrease of CO_2 emissions, which is conditioned to multiple variables, so the fuzzy logic opens a new field of exploration in this topic.
Keywords: Economic development; CO_2 emissions; environmental deterioration; environmental curve; fuzzy logic

Resumen

La situación ambiental es un tema que compete al mundo y el cual debe ser abordado desde diferentes aristas, por esta razón este artículo tiene como objetivo determinar la relación entre desarrollo económico y las emisiones de CO_2 per cápita, según la premisa de Kuznets. Para ello se aplica un modelo econométrico con datos del año 2003-2016, para once (11) países: Alemania, Argentina, Australia, Brasil, Canadá, Chile, China, Colombia, Estados Unidos, Emiratos Árabes y Rusia. Los resultados obtenidos a partir del modelo econométrico empleado confirman parcialmente la relación hipotética planteada por la curva ambiental CAK. Se complementa este hallazgo mediante un modelo de lógica difusa donde se aprecia la variabilidad del comportamiento de las emisiones futuras del CO_2 de acuerdo a la variable de entrada PIB per cápita y CO_2 per cápita. Ambos modelos invitan a comprender la situación ambiental de manera holística, incluyente y creativa. Se concluye que, a partir de los datos usados para los dos modelos el aumento o disminución de emisiones de CO_2, está condicionado a múltiples variables, por lo cual la lógica difusa abre un nuevo campo de exploración en este tema.
Palabras clave: Desarrollo económico; emisiones de CO_2; deterioro ambiental; curva ambiental; lógica difusa

Introduction

The interest and concern for the environmental issue at a global level is growing, evidenced in initiatives such as the 2030 global agenda with guidelines and objectives for the sustainable development of the world. Perhaps, progress on these goals has been slow, however, progress has been made in terms of the design of public policies, academic and scientific developments, measurement instruments, citizen movements and environmental education, as a turning point to achieve a more resilient and sustainable society.

In practice, it has been understood that sustainable development proposes a society that is more respectful of the environment and seeks to ensure a balance between economic growth, the preservation of natural resources and social well-being. Therefore, the development of countries should not only be measured in terms of economic growth, but also in terms of the sustainability of societies. In this sense, the purpose of this article has been to study the relationship between economic development and CO_2 emissions, according to the premise of the Kuznets-CAK Environmental Curve, using an econometric model and a fuzzy logic model.

To validate the hypothesis for the following eleven (11) countries: Argentina, Australia, Brazil, Canada, Chile, China, Colombia, Germany, United States, United Arab Emirates and Russia. Taking the variables: Gross Domestic Product-GDP per capita, urban population, rural population, industrialization, access to electricity, depletion of energy sources, depletion of minerals, carbon dioxide emission damage, transparency rating, accountability, corruption in the public sector, forest area, land area and adjusted savings, in aspects such as: energy sources, minerals, forest resources and carbon dioxide emissions.

In this regard, it is worth highlighting the fact that carbon dioxide (CO_2) levels in the atmosphere reached a new record of 410.5 parts per million in 2019. Preliminary estimates indicate a reduction in annual global emission between 4.2% and 7.5% by 2020 (due to the pandemic effect). However, globally, a reduction in emissions on this scale will not cause atmospheric CO_2 to decrease (World Meteorological Organization-WMO, 2020).

Carbon dioxide remains in the atmosphere for centuries and in the ocean for longer. Hence the importance of understanding that CO_2 will continue to rise at perhaps a slightly reduced rate by 2022. Hence the importance of taking action for planetary sustainability, as long as greenhouse gas emissions do not cease, temperatures will continue to rise, with the largest increase expected for the period 2022-2026 (WMO, 2022).

Specifically, when considering the problem posed and the variables mentioned above, the contribution of this study is to present a method of analysis which allows the synergy between traditional mathematics with the potential of the mathematics of fuzzy sets in order to optimize the study process which is characterized by its complexity when assessing the selected variables and their relationship with future CO_2 emissions. Therefore, this analysis is complemented with a fuzzy logic model supported by the consultation of twenty-eight (28) experts in sustainability, for the formulation of criteria and fuzzy rules for the model, in addition to validating the CAK.

According to Díaz and Morillas (2004), one of the great advantages offered by fuzzy logic is the possibility of using it in a complementary way with other analysis techniques. Likewise, Restrepo and Vanegas (2015), Medina (2006), Blanco-Mesa, Merigó and Gil-La Fuente (2017) state that, the use of fuzzy logic is quite wide, due to the fact that it has a field of application in almost any area of knowledge.

In this sense, the foundation taken to develop fuzzy logic is based on the use of mathematical models to represent subjective notions (Martínez, 2007; Almache, 2013; Vanegas, Botero and Restrepo, 2014), such as, for example, the knowledge of what will happen in the future with respect to CO_2 emissions, therefore this research emphasizes CAK analysis with the theory of fuzzy sets, which through fuzzy functions allows modeling the linguistic variables of future CO_2 emissions as a consequence of the model input variables: CO_2 emissions and GDP per capita using software Matlab (version 9.12), with the Fuzzy Logic Toolbox-FLT tool, to develop Mamdani-type fuzzy inferences, which allow obtaining the parameters that characterize the nonlinear (non-deterministic) future of CO_2 emissions.

To this effect, this study opens a new field of exploration for the environmental issue by considering the modeling of the problem with the application of fuzzy logic tools and econometrics, revealing a complex style of thinking for a complex problem, such as CO_2 pollution.

In this sense, this article presents the results of an empirical investigation and is organized as follows: the first section presents the introduction. In the second section, a review of the literature is made in order to know the different academic positions on the subject. The third section presents the methodological formulation considering the variables under study, aspects of econometrics and the fuzzy inference model, and the fourth section presents the results obtained from the econometric model in addition to describing the modeling by fuzzy inference, according to the objectives set out in this research. Both models give way to the last section which corresponds to the conclusions derived from their analysis.

Literature Review

The Kuznets-CAK Environmental Curve examines the relationship between economic growth and environmental quality. In this logic, in the short term, economic development worsens the environment, but in the long term, above a certain level of income, economic growth causes lower levels of pollution (Falconi, Burbano and Cango, 2016; Moreno and Avendaño 2022).

Under this assumption, the hypothesis put forward by Kuznets (1955), based on a study carried out for a group of developed countries, considers the existence of a relationship, in the form of an inverted U, between growth and inequality in the early stages of an economy's development and the occurrence of a critical point after which inequality is reduced as growth progresses and the economy presents features more characteristic of a capitalist system.

Beckerman (1992) establishes that the inverted U-shaped Kuznets curve is the reflection of a country where the economy is growing and environmental policies are efficient, so that there is a decrease in environmental degradation in the long term, affirming that the best way to improve the environment is through growth. In other words, in the long term it would be more beneficial to get richer, since, according to his approach, there is a relevant correlation between conservation measures and economic income.

This inverted U, has been a widely studied and quite controversial topic, due, on the one hand, to its importance for the definition of public policies and its implication in climate change and, on the other hand, to the lack of consensus as a consequence of numerous studies with different conclusions. These studies with results for and against in addition to the inconclusive ones is perhaps the best sign that the controversy still persists, considering it pertinent to continue studying the subject.

According to Angulo (2010), different investigations show very varied behaviors, even among the same group of pollutants, these differences can be attributed to the estimation methods used, to the set of countries included in the study and perhaps to the use of different variables, in addition to income, considering that, the more variables included in the model, the weaker the model becomes. In accordance with Zilio and Caraballo (2014), this trend of contradictions gave rise to a new version of the hypothesis, known as the Carbon Kuznets Curve-CKC, whose treatment has become decisive in the opinions, debates and controversies that persist on the subject.

On the other hand, there is evidence from researchers who find that the relationship between pollution and income takes the form of an inverted L or an inverted J, indicating that these are weak forms of CAK (Dinda, 2004a; 2004b). Similarly, Clausen and York (2008), Fallahi (2011), Huang, Hwang and Yang (2008), He and Richard (2010) and Yang, He and Shaoling (2014) conclude that the CAK hypothesis is not satisfied.

In this logic, but with different results, Grossman and Krueger (1991), in a study conducted in Mexico, found that sulfur dioxide and smoke have an inverted U-shaped relationship, i.e., pollution increases when income presents low levels, but in the long term it reaches a peak where, as income increases, pollution levels decrease. Likewise, Fosten, Morley and Taylor (2012), using data from the United Kingdom between 1830 and 2002, found evidence on CAK in that country. As did Nasir and Rehman (2011), using data from Pakistan between the years of 1971 and 2011.

Other studies highlight the resilience of ecosystems and the carrying capacity of the land, arguing that, although the curve shows the effectiveness of environmental policy for pollution abatement, the curve is not related to the fundamental characteristics of the environment (Arrow et al, 1995), that is to say, it may be affected by other exogenous factors.

From the same perspective, Díaz and Escárcega (2009) point out that if this inverted U-shaped relationship were due to exogenous factors —not directly related to the economic growth process— Kuznets' hypothesis would not be fulfilled.

In this sense, they state that, the decoupling between income growth and emissions growth is not a systematic consequence of the economic growth process and, therefore, there is no certain level of income from which the pressure on the environment begins to be reduced as a whole (Monreal and Moreno, 2019). In addition, public sector intervention (adopting measures, promoting agreements and planning energy supply, among other aspects) seems decisive in order to achieve a sustained reversal of the driving effect on emissions exerted by the economic growth process itself (a reduction in emissions is possible in a conjunctural manner as a result of specific events, but the fact that it is sustained over time seems to require public intervention).

In correspondence with this reflection, in recent years different researches agree that the best way to take care of the environment is through effective environmental and social policies, in addition to exercising control over natural resources so that they are used correctly, in this way it is possible to achieve economic growth without deteriorating the environment (Correa, Vasco and Pérez, 2005; Moreno, 2008; Legisa and Moreno, 2013; Catalán 2014; Falconi et al., 2016).

Therefore, this article is of interest because it is based on the premise that the development of countries does not consider in its process the paradigm of sustainability, giving emphasis to the economic and not to the conservation of the environment, thus exceeding the limits of the planet. This is why it is important to establish strategic guidelines such as those set out in the Millennium Development Goals (United Nations-UN, 2000) and now with the Sustainable Development Goals-SDGs (UN, 2018), which seek global consensus on where countries should direct their efforts and achieve sustainable development.

Methodology

This mixed research was based on the use of quantitative and qualitative methods, in order to take advantage of the benefits of both paradigms. In this sense, a literature review was made for the first selection of variables for the econometric model (Angulo, 2010; Correa et al., 2005; Díaz, 2007; Fallahi, 2011; Nasir and Rehman, 2011; Zilio and Caraballo, 2014; Catalán, 2014; Falconi et al., 2016). Then, through a deplhi with twenty-eight (28) experts, the variables were refined according to their relevance and impact, leaving the final version as shown below:

Independent variable

- CO_2 emissions (metric tons per capita).

Dependient variables

- *GDP per capita* (US$ at current prices).
- *Urban population* (% of total).
- *Población rural* (% of total).
- *Industrialization, value added* (US$ at current prices).
- *Access to electricity* (% of population).
- *Adjusted savings*: Depletion of energy sources (current US$).
- *Adjusted savings*: Mineral depletion (current US$).
- *Adjusted savings*: Net depletion of forest resources (US$ at current prices).
- *Adjusted savings*: Net national savings (current US$).
- *Adjusted savings*: Carbon dioxide emission damage (current US$).
- *Aquaculture production* (metric tons).
- *Land area* (square kilometers).
- *Forest area* (square kilometers).
- *Forest area* (% of land area).
- *CPIA public sector transparency, accountability and corruption rating* (1 = low to 6 = high).

The way of organizing the data for the econometric model consisted of panel observation for the period 2003-2016, for 11 countries and 16 variables. The data were extracted from the databases of World Bank (s.f.). With this information the first econometric runs are made until the most suitable model is reached. Once the model is reached, the resulting data is taken, reviewed, organized and structured again so that the information is analyzed by means of a Delphi, to determine the input variables of the fuzzy inference model.

The Delphi panel was made up of experts from Colombia (7), France (1), Portugal (3), Spain (3), Venezuela (4), Mexico (6) and Chile (4) for a total of 28 participants. Specialists in the areas of sustainable development, environmental engineering and economics, with broad expertise in environmental and development projects, academically and scientifically accredited, were consulted. Two rounds were carried out, which were considered sufficient for the completion of the process in consensus and stability.

With the resulting information, the data is filtered and hierarchized into empirical regulations to establish new knowledge and design of a fuzzy inference model of Mamdani (1977), using Matlab (versión 9.12), with the variables: CO_2 Emissions - GDP - CO_2 Emissions in the future. This method was chosen because it is better adapted to the type of data available and the way to access them, in addition to its advantages of being intuitive and being able to handle well in the formulation of unstructured and complex problems (Angulo, 2010; Herrera, Romero & Olmos, 2013; Girod, van Vuuren & Hertwich, 2014).

The model was built with the following steps:

1. *Blurring*: Converts system inputs, which are crisp numerical values, into blurred sets by applying a blurring function. The linguistic values and ranges of the variables GDP and CO_2 emissions are determined. Their degree of belonging to the fuzzy sets is determined.
2. *Fuzzy interference and definition of fuzzy rules*: The SI-ENTONCES rules obtained from the experts are established. Human reasoning is simulated by making inference on the received inputs and the stored SI-ENTONCES rules.
3. *Deblurring*: Converts the blurred set obtained in the previous step into a crisp numerical value that can be reused.

For this model, according to the experts, GDP and CO_2 emissions were considered as input variables, and future CO_2 emissions as the output variable; this selection responds to the main variables considered in Knuzet's hypothesis. Leaving for other research the incorporation of the remaining variables, where experts can discover significant relationships between them and CO_2 emissions.

In summary, in this phase of the study, the input variables are grouped with the help of expert criteria and higher level variables are defined according to the CAK, with a set of fuzzy rules for the system and a specific and clear linguistic meaning. The process is repeated until the output variable is reached, with the aim of inferring the conducive or counterproductive behavior of environmental pollution caused by CO_2 emissions.

This model is built on the basis of the experience of experts by relying on the knowledge they have about the system. Thus, the fuzzy sets and linguistic labels considered for GDP are: High income, Middle high income, Middle income, Middle low income and Low income; and for CO_2 emissions per capita are: High and Low.

Results and Discussion

Econometric Method

The econometric estimation is based on numerical data models. The data used in this study were processed using the panel data technique. Panel data allows us to observe the behavior of a dependent variable with respect to a group of independent variables of different individuals and moments in time. Therefore, panel data is a complete econometric technique as it allows combining two different types of data: Cross-sectional data and time series data. Based on the above, the panel data model has the following equation (1).

$$P_i = \begin{array}{c} \mathbf{Y_{it}} = \emptyset_{it} + \emptyset_t + B_1 PIBcápita_{it} + B_2 POBrural_{it} + \\ \ldots + B_3 Ahfe_{it} + B_4 Ahdc_{it} + B_5 Acu_{it} + B_6 Area_{it} + B_7 Trans_{it} \end{array} \quad (1)$$

Where:

Y_{it} = CO_2 Emissions in metric tons per capita of country *i* in year *t*.

$\emptyset_{it}$ = It is the coefficient that absorbs country-specific effects and incorporates country-specific variables such as culture, language, etc.

$\emptyset_t$ = It is a variable that attempts to absorb effects that occur in each year.

PIB_{it} = Per capita gross domestic product of country *i* in year *t*.

POB_{it} = Rural population of country *i* in year *t*.

$Ahfe_{it}$ = Depletion-adjusted savings from energy sources in dollars of country *i* in year *t*.

$Ahdc_{it}$ = Damage-adjusted savings from carbon dioxide emissions in country dollars in year *t*.

Acu_{it} = Metric tons of aquaculture production of country *i* in year *t*.

$Area_{it}$ = Square kilometers of forest area of country *i* at time *t*.

$Trans_{it}$ = Transparency, accountability and corruption rating in the public sector of country *i* in year *t*.

The data used for the development of the econometric model, as indicated above, cover the period from 2003 to 2016, for 11 countries: Argentina, Australia, Brazil, Canada, Chile, China, Colombia, Germany, United States, United Arab Emirates and Russia. The data were collected from the databases of World Bank (s.f.). With the design of the first model we proceeded to carry out the econometric runs.

Models

In the first model, two regressions are performed which are panel data with fixed and random effects, then the Hausman test is applied. The test yields a statistic of –13.33, that is, there is a flaw in the data that causes the asymptotic assumption of the test not to be met. Therefore, it was decided to replace the population variable by its logarithm. Transforming the new equation (2):

$$P_i = \begin{array}{c} \mathbf{Y_{it}} = \emptyset_{it} + \emptyset_t + B_1 \text{PIBcápita}_{it} + B_2 \text{LOGPOBrural}_{it} + \\ \ldots + B_3 \text{Ahfe}_{it} + B_4 \text{Ahdc}_{it} + B_5 \text{Acu}_{it} + B_6 \text{Area}_{it} + B_7 \text{Trans}_{it} \end{array} \quad (2)$$

In the second model, the econometric process is repeated, with the difference that the Hausman test statistic yielded a value of 0; therefore, since this value is less than 0.05, the use of panel data with fixed effects is recommended. Once the econometric model has been identified, a multicollinearity test is performed. Table 1 shows the values obtained for the Variance Inflation Factor Uncentered (VIF Uncentered). It is concluded that this model presents multicollinearity problems.

Table 1.
VIF Uncentererd factor values obtained from model 2.

Variable	VIF	1/VIF
$Trans_{it}$	19.84	0.05
$LOGPOBrural_{it}$	14.11	0.07
$PIBcápita_{it}$	8.76	0.11
$Ahdc_{it}$	7.84	0.12
$Ahfe_{it}$	5.84	0.17
Acu_{it}	5.25	0.19
$Area_{it}$	3.72	0.26

Source: Own elaboration.

Due to the above, it was decided to extract the variable with the highest value of non-centered variance inflation. Then, the new model or model 3 has the following equation (3):

$$P_i = \begin{array}{c} \mathbf{Y_{it}} = \emptyset_{it} + \emptyset_t + B_1 \text{PIBcapita}_{it} + B_2 \text{LOGPOBrural}_{it} + \\ \ldots + B_3 \text{Ahfe}_{it} + B_4 \text{Ahdc}_{it} + B_5 \text{Acu}_{it} + B_6 \text{Area}_{it} \end{array} \quad (3)$$

Again, a comparison is made between the two types of panels. The Hausman test is applied as a product of the comparison and it is obtained that the statistic obtained in this one has a value of zero (0). Therefore, it can be said that fixed effects in panel data are the econometric technique to be used. Regarding the multicollinearity test, the non-centered variance inflation factor, shown in Table 2, did not show multicollinearity problems with any of the variables.

TABLE 2.
VIF Uncentererd factor values obtained from model 3.

Variable	VIF	1/VIF
$Ahdc_{it}$	7.79	0.12
$Ahfe_{it}$	5.61	0.17
$LOGPOBrural_{it}$	5.56	0.17
Acu_{it}	5.23	0.19
$PIBcápita_{it}$	3.79	0.26
$Area_{it}$	3.63	0.27

Source: Own elaboration.

Since model 3 is assumed to be the correct model, we proceed to detail the values obtained in Table 3.

TABLE 3.
Estimation results of the fixed-data panel model.

Numbers of observations		132
Numbers of groups		11
Variable	Coeficient	Statistic t
$Ahdc_{it}$	–0.00000000000494	–5.03***
$Ahfe_{it}$	0.00000000000172	7.35***
$LOGPOBrural_{it}$	–11.49	–17.89***
Acu_{it}	0.0000000463	5.52***
$PIBcápita_{it}$	–0.000072	–2.88***
$Area_{it}$	0.000000257	–0.51

Note: *** significant at 1%, ** significant at 5%, * significant at 10%.
Source: Own elaboration.

Regarding the interpretation of the coefficients it can be said that:

- The rainforest area variable had no significant effect on the emission of metric tons per capita. The countries studied continue to pollute regardless of this factor.
- A percentage increase in the rural population has a negative effect of –11.40 metric tons of per capita CO_2 emission, this may be due to the fact that people residing in the countryside generate fewer pollutants than those located in industrialized cities.

- One dollar allocated to adjusted energy source savings generates a 1.72 × 1011 increase in per capita CO_2 emissions. A significant and negative effect was expected for this variable. However, it would appear that the savings are not sufficient and that further savings measures would be necessar.
- Regarding the variable CO_2 emissions-adjusted savings. One dollar allocated to savings adjusted for carbon dioxide emission damage generates a decrease of –4.94 × 1011 in CO_2 emissions per capita.
- An increase in the metric tons produced by the aquaculture activity generates an increase in CO_2 emissions. The increase per metric ton is 0.00000004. This is partly due to the increase in the fishing fleet; on the other hand, the greater displacement of these fleets over increasing distances due to the scarcity of products.
- Finally, with respect to per capita GDP, an increase of one dollar in a country's per capita GDP generates a decrease in per capita CO_2 emissions of 0.0000272. This result has little explanatory capacity when taking into account that economic growth is not sufficient to reduce environmental deterioration. The study time should be extended to corroborate that the CAK is in the break phase of its decline.

Econometric results show that there are important implications for achieving sustainable development. It cannot be argued that it is possible to reduce CO_2 emissions exclusively through economic growth (increase in GDP); it is necessary to take regulatory measures in environmental and energy matters (Díaz, 2007).

Fuzzy inference modeling

The econometric results made it possible to identify, through surveys of 28 experts, the variables that have the greatest impact on the increase in CO_2. However, this analysis needs to be complemented with a mathematical tool to treat and process information in which inaccurate and imprecise terms are used. Therefore, fuzzy logic is the most appropriate tool for modeling this type of information. This modeling is based on linguistic rules that approximate a function through the relationship of inputs and outputs of the system (Almache, 2013).

What is sought through the use of fuzzy logic is to describe a complex reality, applying flexible models that interpret the incidence of GDP per capita on CO_2 emissions (the main variables of the hypothesis of Kuznets, 1955). To describe such a reality, a model was made according to linguistic rules based on the econometric results of the relationship between GDP per capita and CO_2 emissions per capita, which gradually lead to obtaining information related to the variables of the fuzzy method. Leaving the incorporation of the remaining variables for other research (on the recommendation of the experts).

Fuzzy model results

Fuzzy Inference Systems-BIS are expert systems with approximate reasoning that map a vector of inputs to a unique (scalar) output. They are based on fuzzy logic to perform this mapping (Maguiña, 2010). Taking this into account, the tool Matlab (version 9.12), using the Mamdani method.

For this study, the fuzzy inference system is composed of the following aspects: 1) Fuzzy inference, 2) Fuzzy inference and 3) De-fuzzy inference.

Borrosification

Input data of GDP per capita and CO_2 emissions per capita are taken and the degree of membership in the fuzzy sets is determined, constructing the model in Figure 1. The conversion of these input data to the linguistic values is done by the degrees of similarity of the data to the linguistic variables.

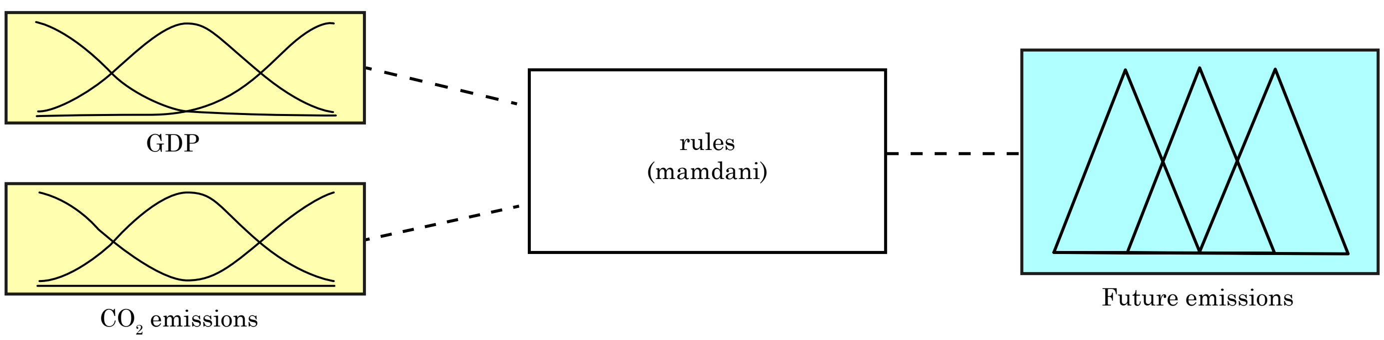

Figure 1. Fuzzy model of future CO_2 emissions.
Source: Own elaboration.

- *GDP per capita*

The World Bank (s.f.) defines GDP per capita as Gross Domestic Product divided by mid-year population. GDP is the sum of the gross value added of all resident producers in the economy plus any taxes on products, minus any subsidies not included in the value of products. It is calculated without deductions for depreciation of manufactured goods or depletion and degradation of natural resources (World Bank, s.f.). The data used for the analysis were US$ at current prices.

According to the above and taking into account the numerical data of the World Bank (s.f.) for the year 2017, values in relation to groups of countries were identified in Table 4, assuming that each category represents a triangular distribution with center at the mean value.

Table 4.
Linguistic values and GDP ranges.

Linguistic variables	Numerical characterization	Established ranges
High income	High-income economies are those in which 2017 per capita was $19 005 or more.	4.5 - 30
Medium high income	Upper-middle-income economies are those in which 2017 GNI per capita was between $5 800 and $19 005.	4.5 - 22.5
Half income	Middle-income economies are those in which 2017 GNI per capita was between $5 800 and $732.	4.5 - 15
Medium low income	Low middle economies are those in which 2017 GNI per capita was between 7 629 and 767	4.5 - 7.5
Low income	Low 767	0 - 4.5

Source: Own elaboration.

- *CO_2 Emissions (metric tons per capita)*

The World Bank (s.f.) defines carbon dioxide emissions as those from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during the consumption of solid, liquid, and gaseous fuels and from gas flaring.

The linguistic variables of CO_2 emissions per capita (Table 5), are related to the world average which is 4.98. The high polluting countries are above this average and those with low pollution are below the average up to 0.30, which is the minimum value found in pollution.

Table 5.
Linguistic values and CO_2.

Linguistic variables	Numerical characterization	Established ranges
High	More than 4.98	11020 43
Low	Between 0.30 to 4.98	0 0 1 5

Source: Own elaboration.

Consequently, the membership functions (Figure 2; Figure 3), are defined from the data entered in the variable editor with respect to the linguistic variables and ranges.

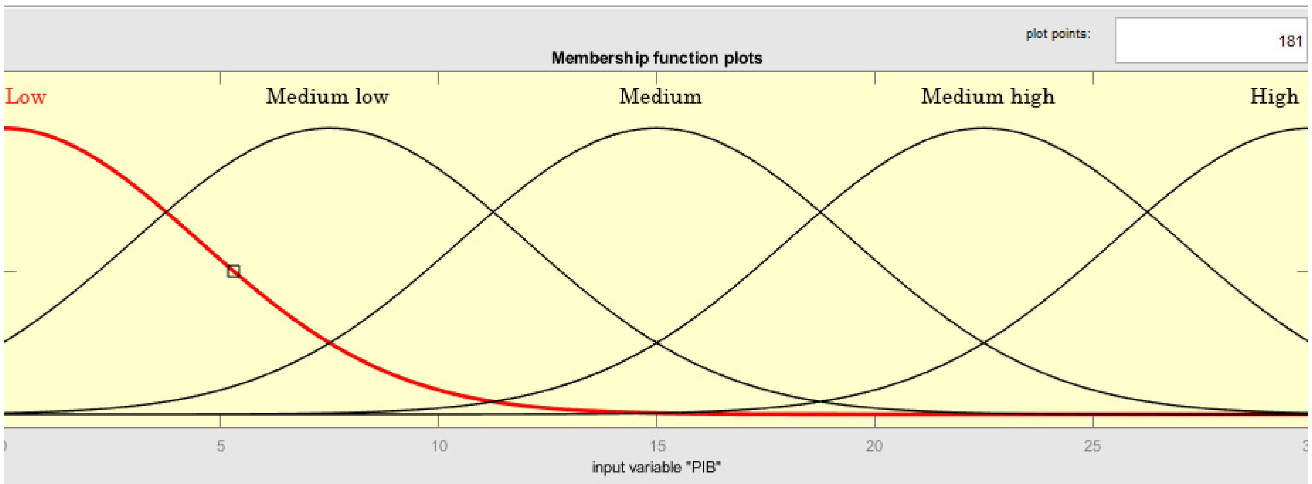

Figure 2. GDP membership function.
Source: Own elaboration.

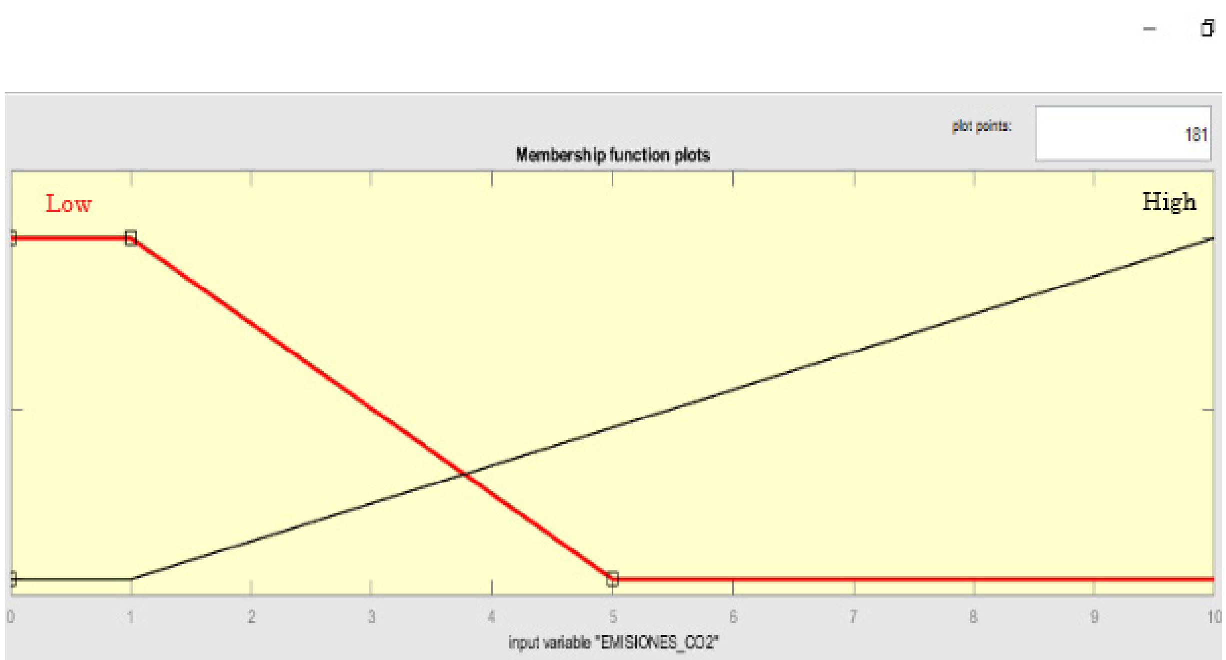

Figure 3. Membership function CO_2 emissions per capita.
Source: Own elaboration.

Fuzzy interference and fuzzy rule definition (BRB)

The behaviors according to the stated variables can be observed in Figure 4, Figure 5, Figure 6, Figure 7 and Figure 8 which were elaborated with data taken from the World Bank (s.f.) from 1990 to 2014. Compliance with CAK is evident, however, the impact of environmental pollution in developed countries cannot be compared in magnitude with respect to lower income countries. This information is considered as a reference to establish the fuzzy rules of the system.

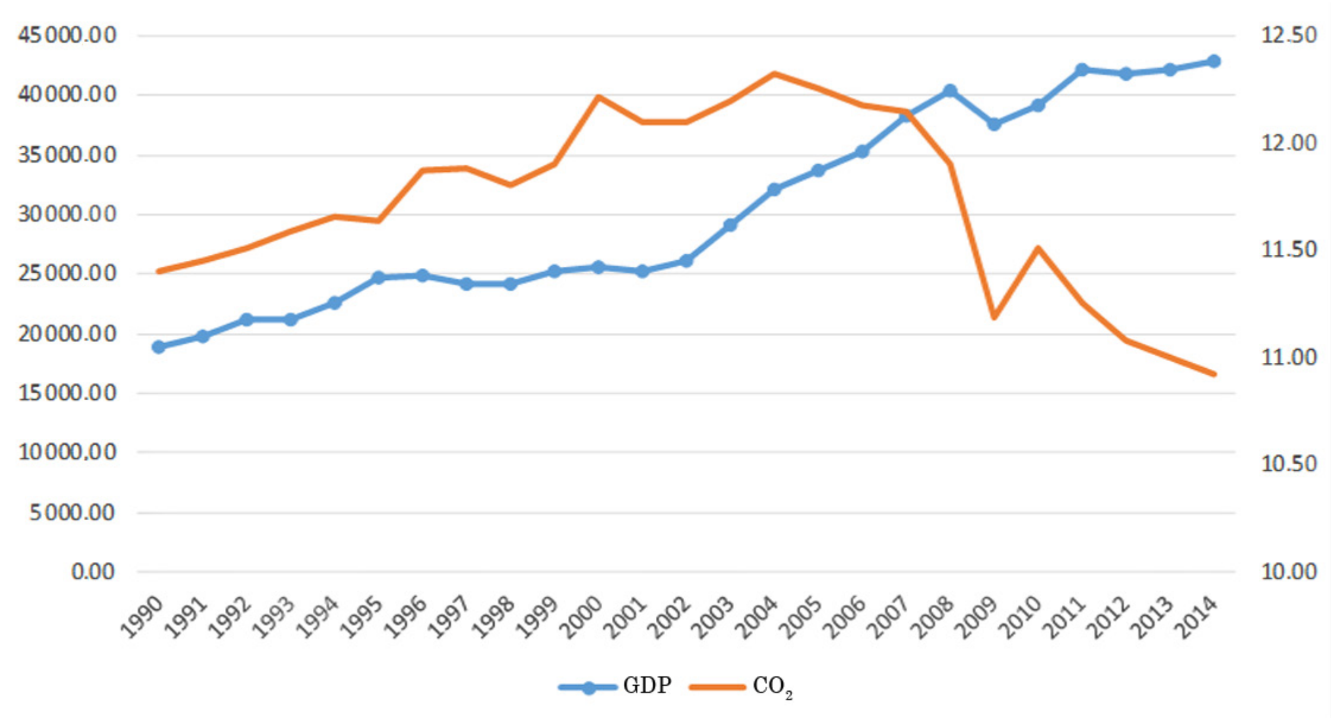

Figure 4. GDP/CO_2 emissions high-income countries.
Source: Own elaboration with data from the World Bank (s.f.).

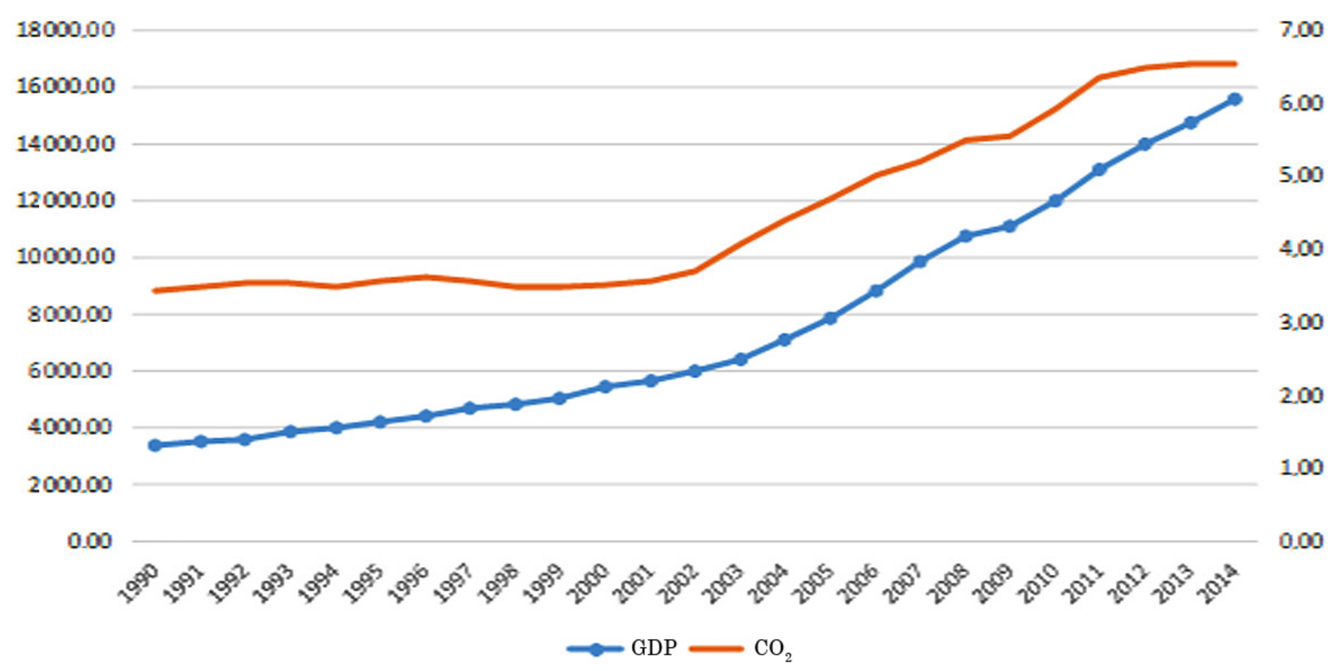

Figure 5. GDP/CO_2 emissions upper middle income countries.
Source: Own elaboration with data from the World Bank (s.f.).

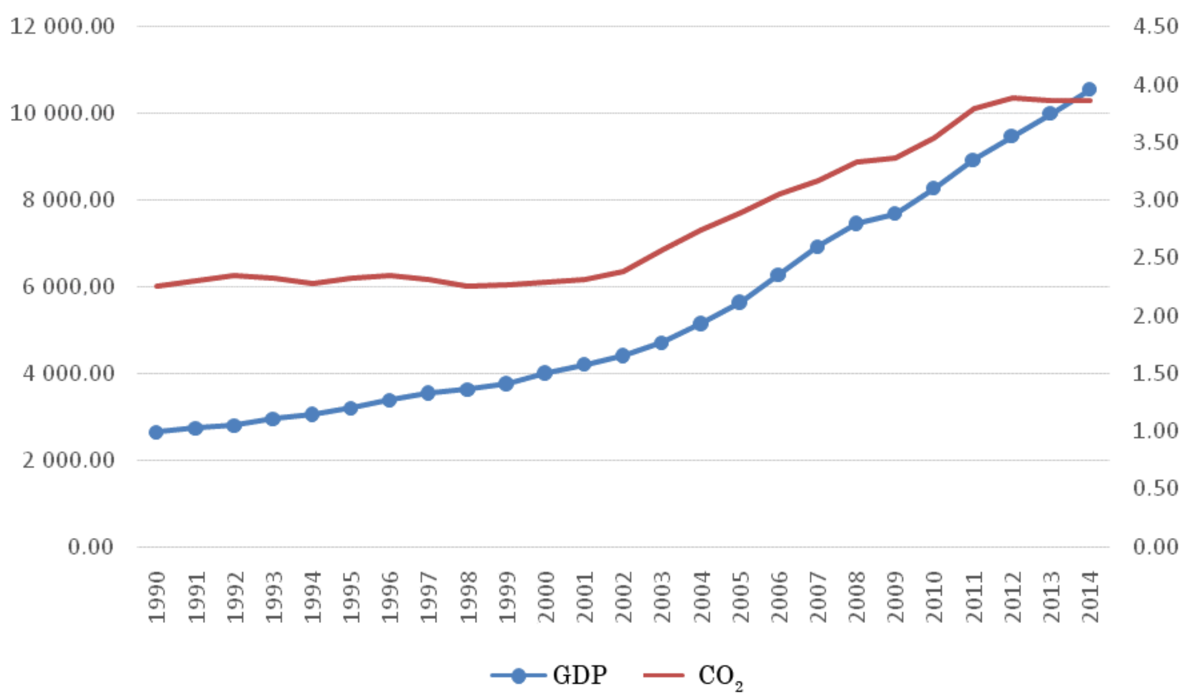

Figure 6. GDP/CO_2 emissions middle-income countries.
Source: Own elaboration with data from the World Bank (s.f.).

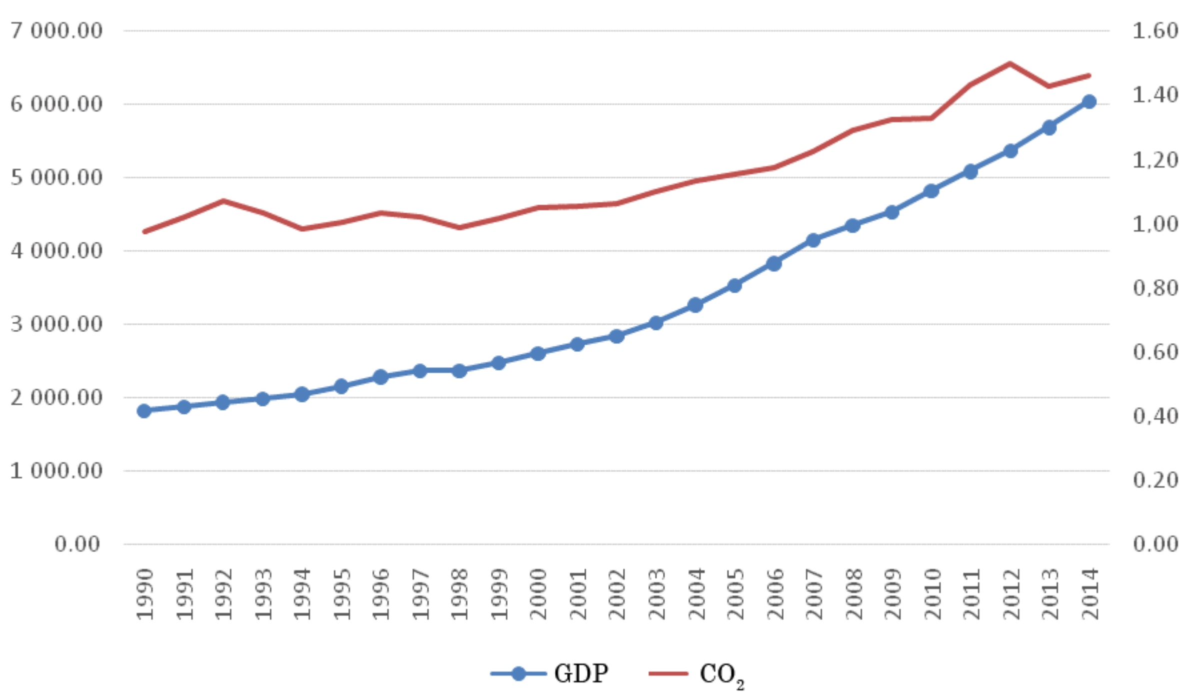

Figure 7. GDP/CO_2 emissions lower middle income countries.
Source: Own elaboration with data from the World Bank (s.f.).

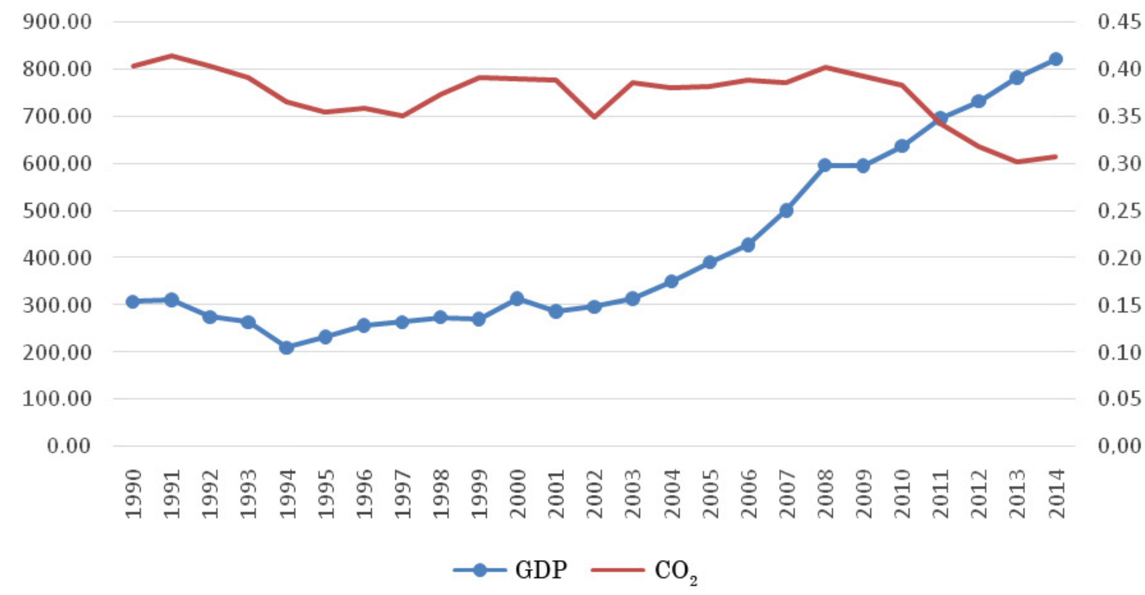

Figure 8. GDP/CO_2 emissions low-income countries.
Source: Own elaboration with data from the World Bank (s.f.).

According to the figures above, CO_2 emissions with respect to income type are decreasing as per capita GDP increases. Likewise, the gaps between CO_2 and income are decreasing in high and low income countries. However, it should be noted that, if high-income countries are compared with low-income countries, this pollution ratio is very high, as shown in Figure 9.

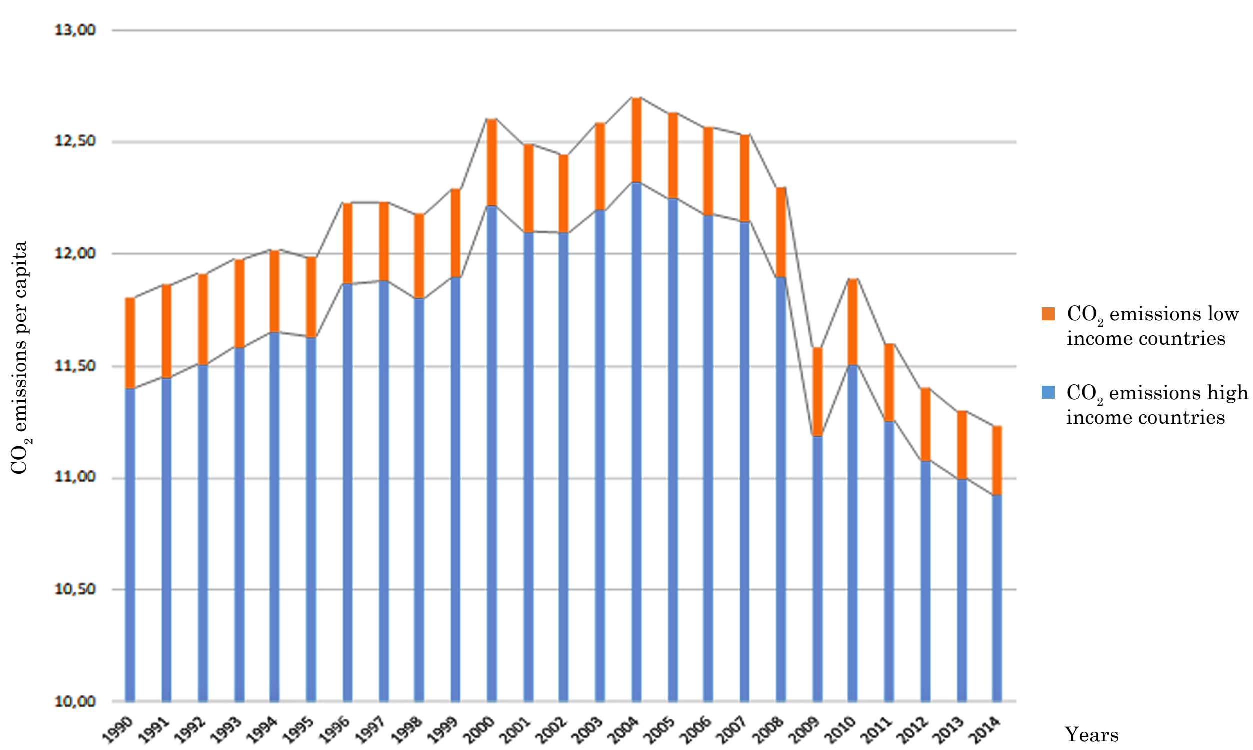

Figure 9. Comparison CO_2 Emissions High vs. low income countries 2009-2014.
Note: Blue bars indicate CO_2 Emission in high-income countries.
Orange bars indicate CO_2 emissions in low-income countries.
Source: Own elaboration.

According to this general analysis and taking into account that fuzzy rules can be defined as the combination of one or more input fuzzy sets called antecedents and to which is associated an output fuzzy set called consequent. It is decided to format the rules with the method Mamdani (1977). If X1 is A1 and X2 is B then U1 is C. Where X1 and X2 are input variables, A and B are linguistic values, that is (high income, low income) U1 is the control variable. That is, they are concrete actions such as increase-decrease.

Thus, the Mamdani rules presented in Table 6. Were made according to the opinion of the experts, considering the econometric results as input, seeking to find the future CO_2 emissions.

TABLE 6.
Fuzzy GDP/CO_2 emissions rules.

Rule	Background GDP/CO_2		Consistent
1	High	High	Will decrease
2	High	Low	Will decrease excessively
3	Medium high	High	There will be no changes
4	Medium high	Low	It will increase
5	Medium	Low	It will increase
6	Medium	High	There will be no changes
7	Low	Low	Will increase excessively
8	Low	High	It will increase

Source: Own elaboration.

These rules were applied in Matlab for deborrosification as shown in Figure 10.

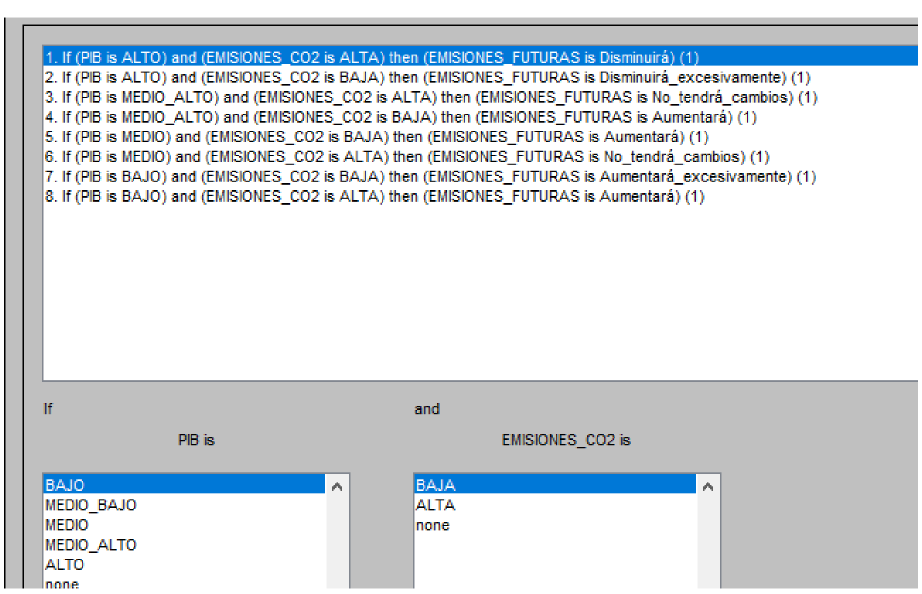

Figure 10. Rules of implication.
Source: Own elaboration.

Desborrosification

Matlab uses the deblurring method in which the output global fuzzy set is integrated algebraically (Figura 11).

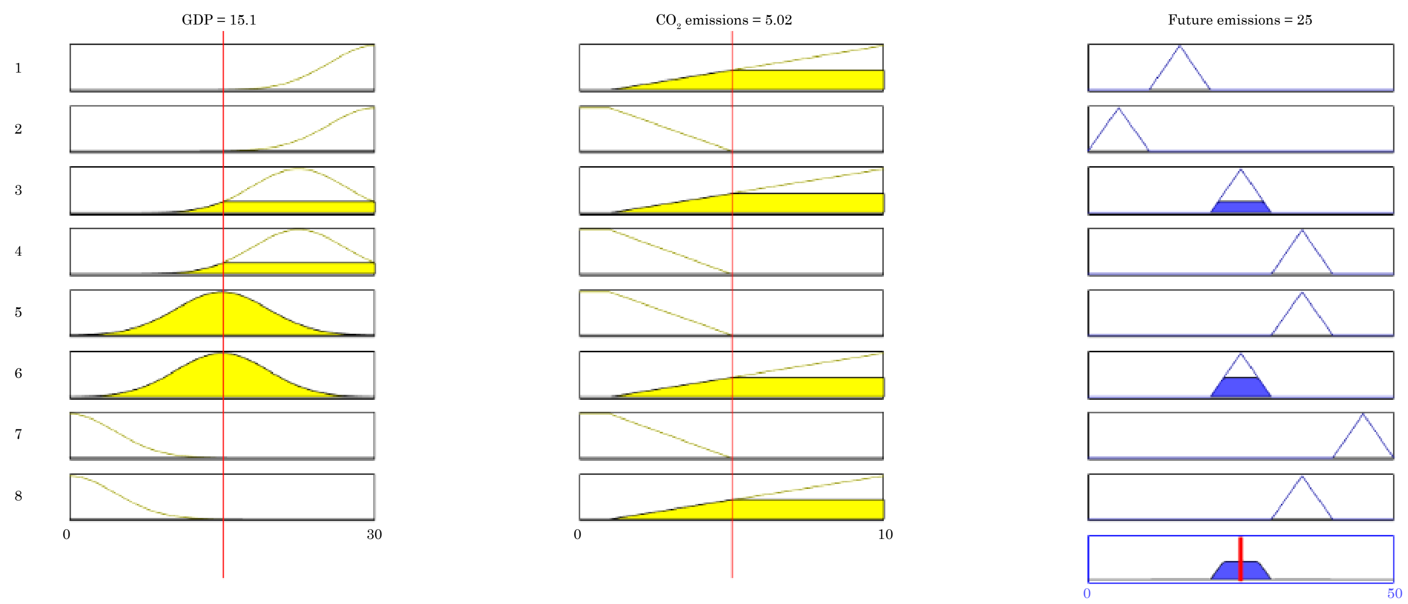

Figure 11. Fuzzy inference system of the fuzzy model Future CO_2 emissions.
Source: Own elaboration.

For the verification of this model, some analyses were made of the results provided by the software. Tabla 7 shows the units of increase according to the situation presented.

Table 7.
Magnification units.

GDP	CO_2 emissions	Results obtained
29.1	0.38	15.1
29.1	5.02	19.5
29.1	9.46	18.6
15.3	5.02	24.9
15.3	9.46	24.9
15.3	0.278	34.7
8	0.648	39.9
8	3.2	34.3
8	4.94	30.3
9	9.46	29.9
3.82	0.28	44.1
3.82	5.28	33.9
3.82	8.17	34.1

Source: Own elaboration.

According to the above, variations occur mainly when GDP increases or decreases, even if pollution is low, a low-income country will increase its pollution. On the contrary, in high-income countries, if their CO_2 emissions decrease, their future emissions will decrease.

Finally, Figure 12 shows that as GDP reaches medium levels and pollution is at medium levels, future pollution reaches medium levels.

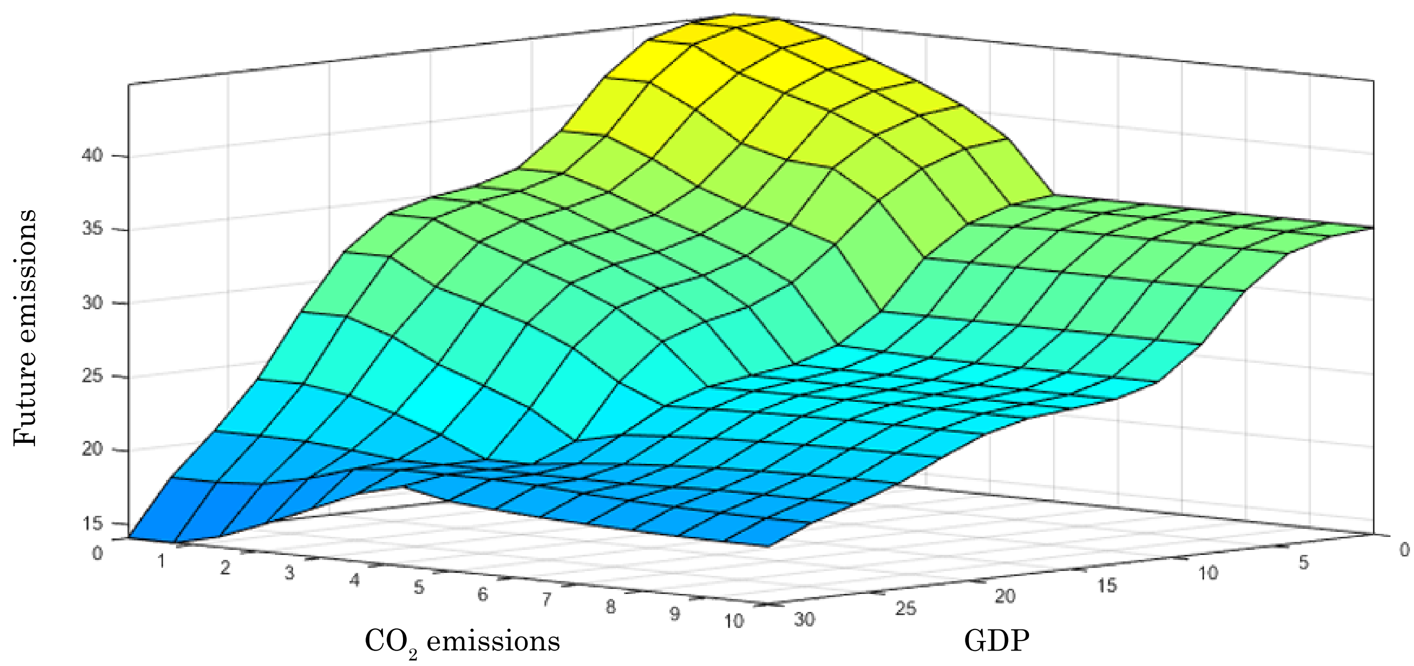

Figure 12. Diffuse surface of the Future CO_2 Emissions model.
Source: Own elaboration.

The results of the model are:

- As current emissions increase and gross domestic product increases, future emissions will decrease and take on a value close to 20.
- In contrast, if future emissions grow, but are accompanied by low CO2 emissions, future CO_2 emissions are high.
- If GDP is at a medium level and current emissions are medium, future emissions are low.
- When GDP is low and emissions are low, it is to be expected that future CO_2 emissions will be too high.
- As GDP reaches average levels and pollution is at average levels, future pollution reaches average levels.
- Knuzet's hypothesis is partially fulfilled, leaving out other predictor variables on the future behavior of CO_2 emissions.

In synthesis, upon analyzing the results obtained in both models, the invitation is to understand that the present environmental situation must be approached in a holistic, inclusive and creative manner. In view of this problem, it is evident that Kuznets' theory is partially fulfilled. The experts consulted believe that economic growth will not necessarily solve environmental problems. On the other hand, they consider that it is an excuse to justify the pollution that the most developed countries have today.

Conclusiones

The arguments of the Kuznets environmental curve have been the subject of numerous empirical analyses, which allow us to evidence its limitations (Clausen & York, 2008; Dinda 2004a; Fallahi 2011; Huang et al., 2008, He & Richard, 2010; Yang & Shaoling, 2015). This study partially confirms the CAK and allows us to understand whether the measures that countries take, in a context of global consensus and agendas to mitigate the impact caused by economic growth/$C0_2$ emissions, are effective or not. Considering that in the current context, policies are required to modify modes of production and consumption towards more sustainable forms with comprehensive strategies to reduce global pollution levels.

On the other hand, the type of pollution, which for this research has been CO_2, a gas that remains for many years in the atmosphere and generates irreversible damage, is considered as a limiting factor in this study, therefore, a CAK is not enough to understand the complex aspect of environmental pollution, consequently, the presence of other gases, such as methane and nitrous oxides, must be considered.

From the data set used in this study, it is concluded that the increase or decrease of CO_2 is conditioned to multiple variables, some of them highlighted in the econometric model developed in this research, which needed to be complemented with a fuzzy logic model to capture the non-linearity of the future behavior of the variables CO_2 per capita and GDP per capita. It is thus demonstrated that both models complement each other to contribute to the formulation of public policies in a context of complexity that requires information on variables that have a high impact on sustainable development. Therefore, fuzzy logic opens a new field of exploration in this topic.

This implies that greater efforts should be made to carry out scientific studies that contemplate the synergy between different models of analysis, in the sense that an attempt was made in this study to establish the existence of the CAK and it is evident that the traditional model is limited when it comes to including variables; variables that cannot be ignored in this subject, so the recommendation is to go deeper into fuzzy logic with the inclusion of more variables that explain the present and future reality in the face of the challenges that sustainable development implies.

Finally, it is emphasized that this recommendation is due to the fact that it has been demonstrated, with the exercise carried out, how the application of fuzzy logic allows dealing with complex problems of highly nonlinear systems. In this case, in spite of having worked with only a few variables, it is pertinent and interesting to show how the variables of a system are treated, establishing fuzzy sets within their range of variation with definition of rules that allow inferring the output of the system.

Statement of Authorship

Avendaño Cárdenas: Conceptualization, research, data curation.
Moreno Freites: Methodology, research, data curation, writing, revising and editing.
Mendoza Crespo: Formal analysis and data curation.

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Conflict of Interest Statement

The present research does not represent any conflict of interest with them, the journal, the publisher and the funding entities.

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